Solid Waste Processing and Resource Recovery Workshop Report Appendix – Volume II

Engineering Directorate
Crew and Thermal Systems Division

CTSD-ADV-474

Revision A
July 1, 2002

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

JSC 40193

CREW AND THERMAL SYSTEMS DIVISION
NASA-LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

Solid Waste Processing and Resource Recovery Workshop Report
Volume II

DOCUMENT NUMBER	DATE
CSTD-ADV-474	July, 2002

PREPARED BY:	Original Signed by: C. Verostko, J. Joshi, M. Alazraki, and J. Fisher
APPROVED BY:	(BRANCH) Original Signed by: B. Sauser
APPROVED BY:	(PROGRAM) Original Signed by: D. Henninger, D. Russo
AUTHORIZED RELEASE BY:	(DIVISION) Original Signed by: S. Poulos

No. of Pages: 236

REVISIONS

REVISION LETTER/DATE	PREPARER	APPROVALS		AUTHORIZED
		BRANCH	PROGRAM	
Revision A/ July 1, 2002	Alazraki			

TABLE OF CONTENTS

PURPOSE OF REVISION (July 2002)

The purpose of this revision was to fix numerous typographically errors found in the original document, and to provide an update on the progress of the Solid Waste Management efforts. Nearly all of the technical information contained in these documents is the same as the original versions. For additional sections, dates were added to distinguish these new sections from the original document.

EXECUTIVE SUMMARY

Supplement July 2002

The purpose of this document was to capture the raw data collected prior to or provided at the Solid Waste Processing and Resource Recovery (SWPRR) Workshop. This document should be used to provide additional detail that is not captured in the summarized workshop report finding - Solid Waste Processing and Resource Recovery Workshop Report - Volume I.

There have been significant improvements within Advanced Life Support (ALS) Solid Waste Processing Group since the initial publication of the SWPRR Workshop Report. First and foremost, the name of our group has changed, from Solid Waste Processing to Solid Waste Management (SWM). The reasoning is SWM more accurately describes the functions that will be needed on future space-based human missions. Solid waste processing will be one of the functions that SWM can provide.

Additionally, no further revisions to this document are foreseen. The reasoning is that the SWM group has been working to develop a criteria evaluation form for SWM technologies. In the future, the SWM technology criteria form will incorporate the information collected in this document. The idea will be to collect data via the criteria sheets electronically. Using this format, the information on a particular SWM technology can be collected, updated, and stored in a database.

OVERVIEW OF WORKSHOP

Supplement July 2002

The purpose of the SWPRR workshop was to collect data on Solid Waste Processing and Resource Recovery Technologies. From this data, it was estimated that a SWP Research and Development (R&TD) plan could be developed.

The charter of the workshop was the following: "*The goal of this WPRR workshop is to provide input to NASA to develop a research and technology development strategy for WPRR. Candidate waste processing technologies for possible use in future space-based human life support systems are to be assessed at this workshop. Each candidate solid waste processing technology is to be independently assessed in terms of established criteria including mass, power, volume, reliability, use of expendables, technology readiness level, and operational scenarios (e.g. microgravity vs. hypogravity; vehicle vs. planetary surface applications).*"

SWPRR WORKSHOP AGENDA

Monday - April 3, 2000

12:30 p.m. - 5:00 p.m.	**Registration to Workshop**
1:00 p.m. - 4:00 p.m.	**NASA Leads and Appointed Group Leads** – Perform a detailed review of workshop objectives and technology assessment plan with group attendee leads on what NASA wants to obtain from the technology assessment and make any minor modifications or changes.

Tuesday - April 4 2000

7:30 a.m. - 5:30 p.m.	**Registration to Workshop**
8:00 a.m. - 8:10 a.m.	**Welcome -** *Albert Behrend, Johnson Space Center*
8:10 a.m. - 8:20 a.m.	**Charge to the Workshop** - *Jitendra Joshi, Universities Space Research Association*
8:20 a.m. - 8:45 a.m.	**Address to the Workshop** - *Joan Vernikos, NASA Headquarters*
8:45 a.m. - 9:30 a.m.	**Advanced Life Support Project Overview** - *Donald Henninger, Johnson Space Center*
9:30 a.m. - 10:15 a.m.	**History on Waste Handling at NASA** • Mercury through Shuttle - *Richard Sauer, Johnson Space Center* • Space Station (U.S. and Russian) - *Hubert Brasseaux, Johnson Space Center*
10:15 a.m. - 10:45 a.m.	**Break**
10:45 a.m. - 11:45 a.m.	**Mission Scenarios and Technology Evaluation Matrix** - *John Keener, Johnson Space Center*
11:45 a.m. - 1:00 p.m.	**Lunch**
1:00 p.m. - 3:30 p.m.	**Groups I to III Begin Assessments** • Group I - Biological • Group II - Physicochemical • Group III - Pre- & Post- Processing
3:30 p.m. - 3:45 p.m.	**Break**
3:45 p.m. - 5:30 p.m.	**Groups Assessments (Continues)**

5:30 p.m. **Adjourn**
(Except NASA Leads and Appointed Group Leads)

5:40 p.m. - 6:00 p.m. **Group Leads Meet to Discuss:**

- Priorities
- Technology Assessment
- Identify Key Issues to Complete Assessments

6:00 p.m. - 7:30 p.m. **Reception**

Wednesday - April 5, 2000

8:30 a.m. - 9:00 a.m. **Solid Waste Considerations Aboard MIR -** *Shannon Lucid, Johnson Space Center*

9:00 a.m. - 9:15 a.m. **Groups Review:**

- Plan with modifications for completing technology assessments
- Key issues and priorities that need to be addressed by each working group
- Any concerns not previously addressed

9:15 a.m. - 10:15 a.m. **Groups I to III Assessments (Continues)**

10:15 a.m. - 10:45 a.m. **Break**
10:45 a.m. - 12:15 p.m. **Groups I to III Assessments (Continues)**

12:15 p.m. - 1:30 p.m. **Lunch**

1:30 p.m. - 4:15 p.m. **Groups I to III Assessments (Continues)**

4:15 p.m. - 4:30 p.m. **Break**

4:30 p.m. - 6:00 p.m. **Groups I to III Assessments (Continues)**

- Complete Assessments
- Preparation of Assessments for Presentation
- Post Workshop Report Deliberations

6:00 p.m. **Adjourn**

Thursday - April 6, 2000

7:30 a.m. - 9:15 a.m.	**Groups I to III Assessments** Complete Presentations
9:15 a.m. – 10:15 a.m.	**Presentation of Assessments (Group 1)** (One hour for each group)
10:15 a.m. – 10:30 a.m.	**Break**
10:30 a.m. – 11:30 a.m.	**Presentation of Assessments (Group 2)**
11:30 a.m. – 12:30 p.m.	**Presentation of Assessments (Group 3)**
12:30 p.m. - 12:45 p.m.	**Concluding Remarks –** *Charles Barnes, NASA Headquarters*
12: 45 p.m. - 2:00 p.m.	**Lunch**
2:00 p.m. - 3:00 p.m.	**Open Discussion**
3:00 p.m.	**Adjourn** *(Except NASA Leads and Appointed Group Leads)*
3:00 p.m. - 3:30 p.m.	**Break**
3:30 p.m. - 5:00 p.m.	**Post-Workshop Report Discussion** *(NASA Leads and Appointed Group Leads)*

UPDATED PARTICIPANT LISTING – CONTACT INFORMATION (7/2002)

Waste Processing and Resource Recovery Workshop
April 4-6, 2000
Nassau Bay Hilton
Houston, TX

James R. Akse, Ph.D.
Umpqua Research Company
P.O. Box 609, 125 Volunteer Way
Myrtle Creek, OR 97457-0102
Phone: 541-863-2653
Fax: 541-863-7775
jakse@urcmail.net

Michael Alazraki
ALS Solid Waste Management Lead
2400 NASA Road 1
Mail Code: C-77
Houston, TX 77058
Phone: 281-483-0004
Fax: 281-483-2508
malazrak@ems.jsc.nasa.gov

James Atwater, Ph.D.
Umpqua Research Company
P.O. Box 609, 125 Volunteer Way
Myrtle Creek, OR 97457-0102
Phone: 541-863-2652
Fax: 541-863-7775
jatwater@urcmail.net

Charles Barnes, Ph.D.
Acting Program Lead
Advanced Human Support Technology Lead
NASA Headquarters, Code UB
300 E Street SW
Washington, DC 20546-0001
Phone: 202-358-2365
Fax: 202-358-4168
cbarnes@hq.nasa.gov

Stephen L. Baylin
NAVSEA Carderock Division
Naval Surface Warfare Center
Code 633
9500 McArthur Blvd.
West Bethesda, MD 20817-5700
Phone: 301-227-5171
Fax: 301-227-5557
baylinsl@nswccd.navy.mil

Albert Behrend, Ph.D. (**RETIRED**)
Mail Code EC, Building 7A, Room 137A
NASA Johnson Space Center

Moshe Ben-Reuven, Ph.D.
Ilene Court, Building 9, Unit 21
MBR Research, Inc.
Hillsborough, NJ 08844
Phone: 908-281-6000
Fax: 908-281-6386
globen_mbr@email.msn.com

Hubert Brasseaux
Mail Code OC, Building 4S
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-244-8079
hubert.j.brasseaux2@jsc.nasa.gov

David P. Chynoweth, Professor
Agricultural and Biological Engineering
Frazier-Rogers Hall, P.O. Box 110570
University of Florida
Gainesville, FL 32611
Phone: 352-392-1864 ext 291
Fax: 352-392-4092
chyn@agen.ufl.edu

Robert M. Cowan, Ph.D.
Senior R&D Engineer / Laboratory Director
The Sapient's Institute
Bioresource Engineering Group, Cook College,
Rutgers University
20 Ag Extension Way
New Brunswick, NJ 08901-8500
Phone: 732-932-8875
Fax: 732-932-7931
cowan@envsci.rutgers.edu

UPDATED PARTICIPANT LISTING (JULY 2002)

Kevin A. Davis, Ph.D.
Suite 210
Reaction Engineering International
77 West 200 South
Salt Lake City, UT 84101
Phone: 801-364-6925 ext. 23
davis@reaction-eng.com

Brian Davison, Ph.D.
Mail Stop 6226, Building 4505
Bioprocessing Research and Development Center
Oak Ridge National Laboratory
Bethel Valley Road, P.O. Box 2008
Oak Ridge, TN 37831-6226
Phone: 865-576-8522
Fax: 865-574-6442
davisonbh@ornl.gov

Richard I. Dick, Ph.D.
118 Hollister Hall
Civil and Environmental Engineering
Cornell University
Ithaca, NY 14853
Phone: 607-255-3648
Fax: 607-255-9004
rid1@cornell.edu

Alan E. Drysdale, Ph.D.
Life Science Project Manager
The Boeing Company
Mail Code 721B-L420
100 Boeing Way
Titusville, FL 32780
Phone: 321-383-2857
Fax: 321-269-6201
alan.e.drysdale@boeing.com

Mike Ewert
Mail Code EC2, Building 7
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-9134
Fax: 281-483-9167
michael.k.ewert1@jsc.nasa.gov

John Feighery
Mail Code EC3
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-7873
john.e.feighery1@jsc.nasa.gov

James M. Fenton, Ph.D.
Chemical Engineering Department
University of Connecticut
191 Auditorium Road, U-222
Storrs, CT 06269-3222
Phone: 860-486-2490
Fax: 860-486-2959
jmfent@engr.uconn.edu

Barry W. Finger
Honeywell, Crew and Thermal Systems Division
NASA Johnson Space Center
Building 7A, Rm. 223, Mail Code EC3.
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-5235
Fax: 281-483-5060
barry.w.finger1@jsc.nasa.gov

Melvin S. Finstein, Ph.D. (**RETIRED**)
105 Carmel Road
Wheeling, WV 26003-1505
Phone: 304-242-0341
Fax: 304-243-2497

John Fisher
Lead Engineer – Life Support
Mail Stop 239-15
Astrobiology Technology Branch
NASA Ames Research Center
Moffett Field, CA 94035-1000
Phone: 650-604-4440
Fax: 650-604-1092
jfisher@mail.arc.nasa.gov

Jay L. Garland, Ph.D.
Mail Code DYN-3
Bioregenerative Research and Technology Development
Dynamac Corporation
Kennedy Space Center, FL 32899
Phone: 321-476-4276
Fax: 321-853-4165
jay.garland-1@ksc.nasa.gov

Joe Genovese
Mail Stop 1A-2-W66
Hamilton Sundstrand
One Hamilton Road
Windsor Locks, CT 06096
Phone: 860-654-5304
Fax: 860-654-2673
joseph.genovese@hs.utc.com

UPDATED PARTICIPANT LISTING (JULY 2002)

Ashwani Kumar Gupta, Ph.D.
2159 Engineering Classroom Building
Department of Mechanical Engineering
University of Maryland
Campus Drive
College Park, MD 20742
Phone: 301-405-5276
Fax: 301-314-9477
akgupta@eng.umd.edu

Anthony J. Hanford, Ph.D.
Environmental Analysis Section, Analyst
Lockheed Martin Space Operations
2400 NASA Road One, Mail Stop C70
Houston, TX 77058
Phone: 281-333-6525
Fax: 281-333-7727
tony.hanford@LMCO.com

Donald Henninger, Ph.D.
Mail Code EC
Crew and Thermal Systems Division
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-5034
Fax: 281-483-5060
dhennin1@ems.jsc.nasa.gov

Duncan Hitchens
Lynntech, Inc.
7610 Eastmark Drive
College Station, TX 77840
Phone: 409-693-0017
Fax: 409-764-7479
duncan.hitchens@lynntech.com

John A. Hogan, Ph.D.
Department of Environmental Sciences
Cook College
Rutgers, The State University of New Jersey
14 College Farm Road
New Brunswick, NJ 08901
Phone: 732-932-3638
Fax: 732-932-8644
hogan@aesop.rutgers.edu

Glenn T. Hong
Senior Technical Specialist
General Atomics
18 Wachusett View Drive
Westborough, MA 01581
Phone: 508-870-0109
glennhong@aol.com

Patrick Craig Hooper, PE
Senior Project Engineer – Environmental Systems
Northrop Grumman Newport News
VASCIC Bldg 904
4101 Washington Avenue
Newport News, VA 23607
Phone: 757-688-0579
Fax: 757-688-4464
hooper_pc@nns.com

Jitendra Joshi, Ph.D.
Deputy Program Manager
NASA Advanced Human Support Technology Program
Universities Space Research Association
300 D Street, SW, #801
Washington, DC 20024
Phone: 202-488-5159
Fax: 202-479-2613
jjoshi@hq.nasa.gov

Harold M. Keener, Ph.D.
Department of Food, Agricultural, and Biological Engineering
1680 Madison Avenue
Ohio Agricultural Research Development Center
Wooster, OH 44691
Phone: 330-263-3856
Fax: 330-263-3670
keener.3@osu.edu

John Keener, Ph.D.
Mail Stop C70
Lockheed Martin Space Operations
2400 NASA Road One
Houston, TX 77058
Phone: 281-333-7086,
Fax: 281-333-7727
john.keener@lmco.com

Mark Kliss, Ph.D.
Chief, Astrobiology Technology Branch
NASA Ames Research Center
Mail Stop N239-15
Moffett Field, CA 94035-1000
Phone: 650-604-6246
Fax: 650-604-1092
mkliss@mail.arc.nasa.gov

Kevin E. Lange
Lockheed Martin Space Operations
2400 NASA Road 1, Mail Code C70
Houston, TX 77058
Phone: 281-333-6049
Fax: 281-333-7727
kevin.lange@lmco.com

Wen-Ching Lee
Lockheed Martin Space Operations
2400 NASA Road One, Mail Stop C-70
Houston, TX 77058
Phone: 281-333-6826
Fax: 281-333-7727
wen-ching.lee@lmco.com

JoAnn S. Lighty, Ph.D.
College of Engineering
Department of Chemical and Fuels Engineering
University of Utah
1495 East 100 South, 214 KRC
Salt Lake City, UT 84112-1114
Phone: 801-581-5763
Fax: 801-581-8692
jlighty@coe.utah.edu

Chin Lin, Ph.D.
Mail Code EC2
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-9126
Fax: 281-483-9167
chin.h.lin1@jsc.nasa.gov

Shannon Lucid
Mail Code CB, Building 4S, Room 6200
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-244-8938
slucid@ems.jsc.nasa.gov

Michael Modell
MIT Laboratory for Energy and the Environment
23 Fresh Pond Place
Cambridge, MA 02138
Phone: 617-547-3147
Fax: 617-864-6628
mmodell@mit.edu

Gene E. Nolting
Naval Sea Systems Command
1333 Issac Hull Ave. SE Stop 5011
Washington Navy Yard
Washington, DC 20376-5011
Phone: 202-781-3175
Fax: 202-781-4571
noltingee@navsea.navy.mil

Nigel Packham, Ph.D.
Mail Code EC3
Crew and Thermal Systems Division
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-5138
nigel.packham1@jsc.nasa.gov

Duane L. Pierson, Ph.D.
Mail Code SD3, Building 37, Room 119A
Biomedical Research Laboratories Branch
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-7166
Fax: 281-483-3058
dpierson@ems.jsc.nasa.gov

Mark Pondelick
Envirovac, Inc.
1260 Turret Drive
Rockford, IL 61115
Phone: 815-639-7758
Fax: 815-654-8306
MPONDELICK@EVAC.COM

Tim Rivers
MSE Technology Applications, Inc.
200 Technology Way
Butte, MT 59701
Phone: 406-494-7406
Fax: 406-494-7230
trivers@mse-ta.com

John Sager, Ph.D.
Biological Sciences Branch
Mail Code YA-D3
Spaceport Engineering & Technology Directorate
Kennedy Space Center, FL 32899
Phone: 321-476-4270
Fax: 321-853-4165
john.sager-1@ksc.nasa.gov

Richard L. Sauer, Ph.D. (**RETIRED**)
Mail Code SD2
NASA Johnson Space Center
2101 NASA Road One

George M. Savage
CalRecovery, Inc.
1850 Gateway Blvd., Suite 1060
Concord, CA 94520
Phone: 925-356-3700
Fax: 925-356-7956
GSavage@calrecovery.com

Michael A Serio, Ph.D.
Advanced Fuel Research, Inc.
87 Church Street
East Hartford, CT 06108
Phone: 860-528-9806 ext. 105
Fax: 860-528-0648
mserio@afrinc.com

Richard F. Strayer, Ph.D.
Mail Code DYN-3
Dynamac Corporation
Kennedy Space Center, FL 32899
Phone: 321-476-4274
Fax: 321-853-4165
strayrf@kscems.ksc.nasa.gov

Terry Tri
Mail Code EC
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-9234
Fax: 281-483-5060
ttri@ems.jsc.nasa.gov

Joan Vernikos, Ph.D. (**RETIRED**)
NASA Headquarters
Washington, DC 20546-0001

Charles Verostko
Mail Code EC3
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-9228
Fax: 281-483-5060
cverostk@ems.jsc.nasa.gov

James L. Walsh
039 O'Keefe Building
Georgia Institute of Technology
Atlanta, GA 30332-0837
Phone: 404-894-8054
Fax: 404-894-2184
jw26@eoeml.gtri.gatech.edu

<u>Logistical Staff</u>

Joy King
InDyne, Inc.
300 D Street, SW, Suite 801
Washington, DC 20024
Phone: 202-488-5147
Fax: 202-479-2613
jking1@hq.nasa.gov

Crystal Rucker
InDyne, Inc.
300 D Street, SW, Suite 801
Washington, DC 20024
Phone: 202-488-5145
Fax: 202-479-2613
crucker@hq.nasa.gov

Chantel Whatley
Mail Code EC
NASA Johnson Space Center
2101 NASA Road One
Houston, TX 77058
Phone: 281-483-4390
Fax: 281-483-5060
cwhatley@ems.jsc.nasa.gov

<u>Technical Staff</u>

Rachel Miller
InDyne, Inc.
300 D Street, SW, Suite 801
Washington, DC 20024
Phone: 202-488-5132
Fax: 202-479-2613
rmiller1@hq.nasa.gov

BACKGROUND INFORMATION

Supplement July 2002

The background information included in the upcoming pages was required prior to the SWPRR workshop. The background information includes mission scenarios, a waste model based on the mission scenario, technology readiness level chart, and a technology evaluation form to capture relevant information on potential SWPRR technologies. This information was included here for better understanding of what needs to be developed prior to a workshop.

Background information updates

For the latest information on ALS mission scenarios, please refer to the latest version of the SIMA Reference Mission Document (RMD) JSC-39502A. The RMD gives better description of the overall life support architecture than was available at the time of the SWPRR workshop. For each of the missions outlined in the RMD, the ALS Solid Waste Management working group plans to develop waste models to characterize the wastes, as well as estimate both the rate and schedule at which these wastes are produced. Finally, the information captured in the original workshop technology assessment form has been changed and developed into a new document. The Solid Waste Management Technology Criteria Form will be used from now on to capture information relevant to potential SWM technologies.

MISSION SCENARIOS

For the following scenarios, it was assumed that no useable natural resources are available. While there will probably be a minimal amount of certain natural resources, these were not considered when assessing the technologies. However, technologies were not removed from consideration because they have a low return in some resource areas. **Notice: In the future, please refer to the SIMA Reference Mission Document (JSC#39502-Revision A) for the description of mission scenarios.**

Scenario 1 - Transit Portion
There are approximately 180 transit days from Earth to Mars each way. Food is grown in a minor growth chamber.

Scenario 2 – Independent Exploration Mission (Salad Machine)
This is for an approximately 600-day stay on Mars. A single Mars Transit Vehicle would be used to get to and from Mars. The Combo Lander vehicle contains a habitat and the ascent vehicle. The habitat is destroyed when the ascent vehicle leaves Mars.

Scenario 3 – Concentrated Exploration Mission (One Growth Chamber)
This is for an approximately 600-day stay on Mars per mission. Since the concentrated mission promotes building up the infrastructure, having a plant chamber to grow food becomes a reality. This chamber would be responsible for growing more than just garden crops, and grown food would be the primary diet.

Scenario 4 – Extended Base (Use all plants menu)
This scenario mimics an Extended Mars Base. It involves a stay of more than 10 years. This configuration grows a multitude of plants, which are utilized for more than 75% of the diet.

Scenario 5 – Extended Base (All plant menu)
Again, this scenario mimics an Extended Mars Base with a stay of more than 10 years. This configuration relies on plants for nearly all of the diet. This will yield an upper limit of the amount of inedible mass that needs to be handled.

WASTE MODEL

Background
The waste model developed in the 1991 Resource Recovery Workshop [1] was evaluated using the present exploration missions as operational scenarios. The reference missions were developed from the data in the draft reference mission's document [2] along with the Baseline Values and Assumptions Document, BVAD [3].

Reference Missions
The **MISSION SCENARIOS** are described in a previous section. Listed below are some of the estimated waste generated and potential resources that can be recovery for each of the mission scenarios. For additional details, please refer to **TABLE 1**. Actual waste generation will be highly mission dependent. Prior to determining what potential resources will be recovered, system level analysis will need to be preformed to support the recovery of resources. The amount of food grown per mission scenario is shown in **Figure 1. Note: The food closure outlined in this document has been highly disputed item among the ALS community and these values should be considered overly optimistic. For the most accurate information relevant to the ALS missions, please consult the latest versions of both the BVAD and the RMD.**

Scenario 1 - Transit Portion
Since little food is grown, the primary waste will consists mainly of packaging, although there will be feces and plant biomass to consider. Water is probably the only resource recovered from the waste stream. Carbon dioxide is probably not required and nutrient recovery would be minimal.

Scenario 2 – Independent Exploration Mission (Salad Machine)
The independent mission could be used to test food growth through use of a Salad Machine. At this low food growth, humans provide more than adequate carbon dioxide to allow the plants to grow. Packaging will be the main source of waste. The resources that merit recovery are water and possibly salts.

Scenario 3 – Concentrated Exploration Mission (One Growth Chamber)
The concentrated mission promotes building up of infrastructure; a plant chamber to grow food becomes a more realistic option. This chamber would be responsible for growing more than just garden crops, and grown food would provide a significant dietary contribution. At this food growth level, humans should still provide enough carbon dioxide to allow the plants to grow. Again, the resources that merit recovery are water and possibly salts.

Scenario 4 – Extended Base (All plants menu)
This scenario mimics an Extended Mars Base. It postulates a stay of more than 10 years. This configuration grows a multitude of plants but still relies on packaged food for a quarter of the diet. The amount of carbon dioxide that is produced by the crew is close to the level the plants need. Depending on the exact mix of crops, there may be a surplus or a deficit of carbon dioxide. If a deficit exists, processing for carbon dioxide may be necessary. Water should be recovered if possible (plants at this level of growth might recycle most of the water). Recovery of salts is probably also a needed resource.

Scenario 5 – Extended Base (All plant menu)
Again, this scenario mimics an Extended Mars Base with a stay of more than 10 years. This configuration tries to rely almost wholly on plants for the majority of the diet. This will yield an upper limit on the amount of inedible mass that needs to be handled.[1] Water should be recovered if possible (plants at this level of growth might recycle most of the water). Carbon dioxide should be recovered and so should the salts.

Potential resources:
Some useful products of solid waste processing include nitrogen (make-up gas), water, carbon dioxide, nitrates and the inorganic portion (salts) of the nutrient solution. All of these constituents would depend on the mission. Considerations would be (1) how much of the product can be assimilated by the crew or supporting processes, (2)

---

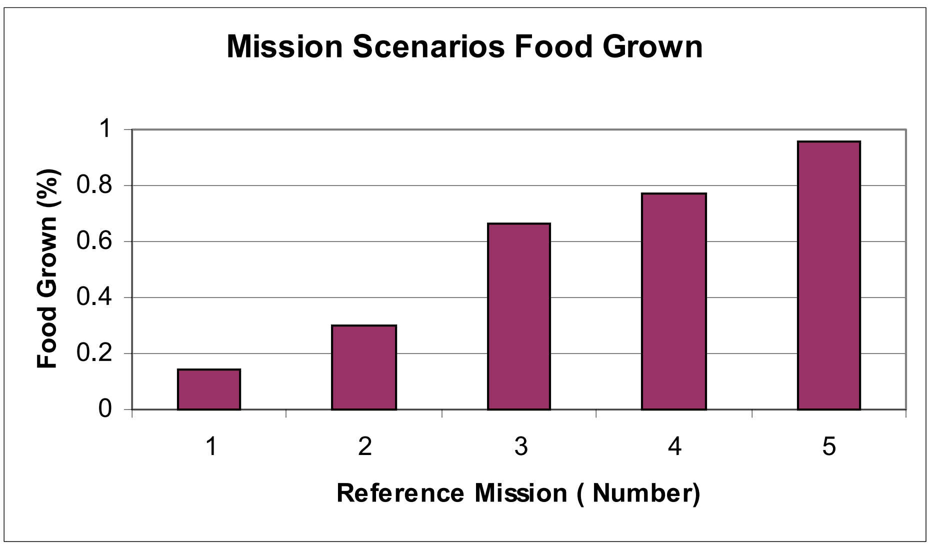
[1]This case postulates growing a greater proportion of the diet on site than current crop mixes can support due to nutritional limitations of a limited crop mix. However, as a study case this scenario has validity, as greater variety may be available in future crop mixes.

what are the requirements for nitrates and salts, and (3) what is the availability of carbon dioxide from other resources. Other byproducts that should be considered are nitrogenous oxides, sulfurous oxides, carbon monoxide, and gaseous hydrocarbons.

While on some missions packaging may represent the largest mass, human waste (feces) and plant biomass should be considered for such items as biohazard and fungal growth. Although water may be reclaimed out of such wastes, this water would need to be further processed for use in a water recovery system. While this workshop does not address purification of water, it may be a consideration for certain processes. Again this points to the need for system level modeling to be preformed, to help make determination on what is the best system level approach to solving problems.

From the perspective of the waste model, the reference missions differ in terms of mission length and mass of biomass generated. Reference missions 3 and 4 were developed from the Baseline Value Assumptions Document (BVAD). Reference mission scenario #1, 2, and 5 were assumed to provide 15%, 30% and 95%, by mass, of the food from growth chambers on site respectively. The percentage of food grown for these reference missions is depicted in Figure 2 below.[2]

Figure 1: Percentage of Food Grown for Different Mission Scenarios



One of the major discriminators in the trash model for these reference missions was the amount of inedible plant biomass produced for each mission. For this study the assumption was made that 10% of the packaged food brought would be considered as inedible plant biomass in the form of table scraps.

The diets for mission scenarios # 1 & 2 used significant amounts of packaged foods, but provided a portion of the diet to be supplemented via a salad machine. Both mission scenario #1 & 2, used scaled-back carbohydrate diets outlined in the BVAD. For mission scenarios # 3 - 5, the two diets documented in the BVAD were used - an all crop diet and a carbohydrate diet. The carbohydrate diet was considered for the crop-produced portion for mission scenario #3, while the all crop diet was assumed for mission scenario #4. Mission scenario #5 additionally increased the percentage of plants grown, to over 90% food closure. The amount of inedible plant biomass was estimated by taking the ratio inedible biomass to total biomass grown for each diet and multiplying this to the respective reference mission's grown food to determine each mission's inedible plant biomass.

[2] **Note:** The food closure outlined in this document has been highly disputed item among the ALS community and these values should be considered overly optimistic. For the most accurate information relevant to the ALS missions, please consult the latest versions of both the BVAD and the RMD.

WASTE MODEL

The waste model is presented below. Packaging material is assumed for all packaged food, which decreases proportionally as the packaged food decreases.

TABLE 1: Waste Model for Six-Person Crew

Units are kg/day (based on 6 person crew)					
Waste Component	Transit, Packaged Food & Salad Crops	Independent Exploration, salad crops grown	Exploration Mission, Low carbohydrate diet	Extended Base, All plants menu	Extended Base, All plants menu
Dry Human Waste	0.720	0.720	0.720	0.720	0.720
Inedible Plant Biomass (1)	1.691	2.247	5.450	7.503	13.820
Trash	0.556	0.556	0.556	0.556	0.556
Packaging Material (2)	7.908	4.721	2.017	1.493	0.408
Paper	1.164	1.164	1.164	1.164	1.164
Tape	0.246	0.246	0.246	0.246	0.246
Filters	0.326	0.326	0.326	0.326	0.326
Miscellaneous	0.069	0.069	0.069	0.069	0.069
Waste Stream Sub Total	**12.68**	**10.05**	**10.55**	**12.08**	**17.31**
Grown Food (without Water)	0.600	1.800	6.000	7.500	14.172
Water in Grown Food	1.260	3.780	12.600	13.200	24.948
Packaged Food	11.760	7.020	3.000	2.220	0.606
Food Sub Total	**13.62**	**12.60**	**21.60**	**22.92**	**39.73**
Mission Duration	180 days	600 days	600 days	10 years	10 years

Notes:
(1) Inedible plant biomass is calculated from the BVAD diet as Inedible Biomass/Average Consumption x Mass of Grown Food and plus 10% of the Packaged Food to represent table scraps.
(2) Packaging material was calculated by taking the ratio of packaging material to packaged food for the transit mission, then multiplying the packaged food for each of the other missions by this ratio.

This data was checked against the ISS trash plan. Between flights 5A and 6A, the plan calls for the total trash generated to be 737.5 kg for 2 crews [5]. The trash model results show between 1.7 and 2.9 kg/person-day. This compares with 3.3 kg/person-day based on 113 days between flights 5A and 6A.

The mass of the air filters was derived from the ISS data [7] by assuming all air filters would be changed out once a year. The mass of each filter is documented as 2.15 kg. Since these filters are HEPA filters, the HEPA line item was deleted from the 1991 workshop data.

The dry component of human waste changes as a function of diet. Since this variation is a fairly small and is not quantified, this component is assumed constant for the different diets.

Table 2: Human Component (Dry Weight)

	kg/(person•day)	lb_m/(person•day)
Feces	0.03	0.07
Urine	0.06	0.13
Shower/Hand Wash	0.01	0.02
Sweat	0.02	0.04
Total	*0.12*	*0.26*

Table 3: Inedible Plant Biomass (Dry Weight)

	kg/(person•day)	lb_m/(person•day)
Protein	0.25	0.56
Carbohydrate	0.29	0.64
Lipids	0.07	0.16
Fiber	1.09	2.41
Lignin	0.11	0.24
Total [3,4]	*1.82*	*4.01*

Table 4: Trash

	kg/(person•day)	lb_m/(person•day)
Clothes/Towels	0.0007	0.0015
Toilet Paper [5]	0.0230	0.0507
Pads/Tampons [5]	0.0035	0.0077
Menstrual Solids [5]	0.0004	0.0009
Paper [5]	0.0650	0.1433
Total	*0.0926*	*0.2041*

Table 5: Packaging Material Trash[6,7]

	kg/(person•day)	lb_m/(person•day)
Snack Packaging	0.060	0.132
Food Containers [8]	0.470	1.036
Plastic Bags [8]	0.060	0.132
Food Remains [9]	0.100	0.220
Frozen	0.050	0.110
Refrigerated	0.020	0.044
Ambient	0.410	0.904
Beverage [10]	0.128	0.282
Straws	0.020	0.044
Total	*1.318*	*2.906*

[3] Hanford, A. J. and Drysdale, A.E. (1999) “Baseline Values and Assumptions Document.” JSC 39317
[4] The inedible plant biomass values here are upper limits. In other words, these values reflect a life support system architecture in which all food is supplied from crops grown on site.
[5] Cellulosic
[6] Grounds, P. (1991) “STS-35 Trash Evaluation Final Report,” NASA JSC-SP-90-2.
[7] The packaging material values here are upper limits. In other words, these values reflect a life support system architecture in which all food is prepared before launch and supplied in individual serving packages.
[8] Polyethylene
[9] The composition is 25% protein, 51% carbohydrate, 8% lipid, and 16% fiber.
[10] Grounds, P. (1991) “Beverage Pouches,” NASA TM SP4-91-081, 4 June 1991.

Table 6: Paper Trash

	kg/(person•day)	lb_m/(person•day)
Wipes	0.14	0.309
Tissues	0.02	0.044
Facial Tissues	0.03	0.066
Waste	0.004	0.009
Total	*0.194*	*0.428*

Table 7: Tape

	kg/(person•day)	lb_m/(person•day)
Masking	0.002	0.004
Conduit	0.004	0.009
Duct	0.035	0.077
Total	*0.041*	*0.090*

Table 8: Filters

	kg/(person•day)	lb_m/(person•day)
Air [11]	0.0244	0.054
Prefilters	0.03	0.066
Total	*0.0544*	*0.120*

Table 9: Miscellaneous

	kg/(person•day)	lb_m/(person•day)
Teflon	0.011	0.024
PVC	0.0005	0.001
Total	*0.0115*	*0.025*

[11] ECLSS Architecture Description Document, Volume 2, Book 2, Revision A, ISS air filters (2.15 kg each, 29 total)

Table 10: BVAD All Crop Diet

Inedible biomass calculation - Based on 20-day diet using all crops (BVAD)

Crop	*Average Consumption [kg/person•day]	Harvest Index	Inedible Biomass [kg/person•day]
Soybean	0.086	0.37	0.146
Wheat	0.24	0.4	0.360
White Potato	0.2	0.7	0.086
Sweet Potato	0.2	0.7	0.086
Rice	0.029	0.4	0.044
Peanut	0.013	0.27	0.035
Tomato	0.22	0.48	0.238
Carrot	0.041	0.9	0.005
Cabbage	0.0038	0.9	0.000
Lettuce	0.024	0.95	0.001
Dry Bean	0.013	0.37	0.022
Celery	0.013	0.7	0.006
Green Onion	0.048	0.5	0.048
Strawberry	0.016	0.4	0.024
Peppers	0.049	0.4	0.074
Pea	0.0075	0.37	0.013
Mushroom	0.0011	0.5	0.001
Snap Bean	0.01	0.37	0.017
Spinach	0.04	0.8	0.010
Crop Sub Total	*1.2544*		*1.215*
Water	*2.2		
Resupplied Food Stuffs	0.37		0.037
Total	*3.82*		*1.25*

*The values given for each crop is a dry weight. Water value of 2.2 kg/person-day represents water used for hydration, cooking and food preparation.

Table 11: BVAD Carbohydrate Crop Diet

Inedible biomass calculation- Based on 20-day diet using Carbohydrate crops (BVAD)

Crop	*Average Consumption [kg/person•day]	Harvest Index	Inedible Biomass [kg/person•day]
Soybean	0	0.37	0.000
Wheat	0.22	0.4	0.330
White Potato	0.17	0.7	0.073
Sweet Potato	0.18	0.7	0.077
Rice	0	0.4	0.000
Peanut	0	0.27	0.000
Tomato	0.21	0.48	0.228
Carrot	0.04	0.9	0.004
Cabbage	0.0025	0.9	0.000
Lettuce	0.021	0.95	0.001
Dry Bean	0.013	0.37	0.022
Celery	0.0075	0.7	0.003
Green Onion	0.034	0.5	0.034
Strawberry	0	0.4	0.000
Peppers	0.031	0.4	0.047
Pea	0.0038	0.37	0.006
Mushroom	0.0013	0.5	0.001
Snap Bean	0.01	0.37	0.017
Spinach	0.04	0.8	0.010
Crop Sub Total	*0.9841*		*0.854*
Water	*2.1		
Resupplied Food Stuffs	0.5		0.005
Total	*3.58*		*0.90*

*The values given for each crop is a dry weight. Water value of 2.1 kg/person-day represents water used for hydration, cooking and food preparation.

Waste Water Component
(Human component included for reference)

Table 12: Waste Water

	kg/(person•day)	lb_m/(person•day)
Urine	1.04	2.29
Shower [12]	5.44	11.99
Hand Wash [12]	1.81	3.99
Metabolic Water [13]	0.36	0.79
Perspiration /Respiration	1.81	3.99
Clothes Wash [14]	12.50	27.56
Urinal Flush	0.49	1.08
Fecal Water	0.09	0.20
Humidity Condensate [15]	0.52	1.15
Dish Wash	5.40	11.90
Total	*29.46*	*64.95*

Table 13: Summary Waste Model (Per crew person)
Units are kg/(person•day)

Waste Component	Transit, All Packaged Food	Independent Exploration, salad crops grown	Exploration Mission, Low carbohydrate diet	Extended Base, All plants menu	Extended Base, All plants menu
Dry Human Waste	0.120	0.120	0.120	0.120	0.120
Inedible Plant Biomass	0.282	0.375	0.908	1.250	2.303
Trash	0.093	0.093	0.093	0.093	0.093
Packaging Material	1.318	0.787	0.336	0.249	0.068
Paper	0.194	0.194	0.194	0.194	0.194
Tape	0.041	0.041	0.041	0.041	0.041
Filters	0.054	0.054	0.054	0.054	0.054
Miscellaneous	0.012	0.012	0.012	0.012	0.012
Total	**2.11**	**1.67**	**1.76**	**2.01**	**2.88**
Grown Food (no Water)	0.100	0.300	1.000	1.250	2.362
Water in Grown Food	0.210	0.630	2.100	2.200	4.158
Packaged Food	1.960	1.170	0.5	0.370	0.101

The grown and packaged food quantity was obtained from the BVAD for scenarios 3 and 4. Scenario 1 packaged food amount was based on the ISS food requirement since the grown food is not nutritionally significant in this scenario. The grown food for scenario 1 was assumed to be 10% of the exploration mission grown amount.

[12] Shower and Hand Wash soap is 0.010 kg/(person•day)
[13] This is a by-product of human metabolic action on consumed food.
[14] Clothes Wash soap is 0.025 kg/(person•day).
[15] Hygiene latent water, 0.43 kg/(person•day), food preparation latent water, 0.03 kg/(person•day), and laundry latent water, 0.06 kg/(person•day)

The amount of water contained in the food grown was assumed to be 67.7% for scenarios 1-3 and 63.8% for scenarios 4-5 (taken from BVAD diets). Scenario 2 packaged food was assumed to be 60% of the ISS food assumption (this should probably be 70% for complete nutrition).

Scenario 5 packaged food is assumed to be 5% of the ISS assumption (with round-off). The grown food was determined by extrapolating the trend of the third and fourth scenarios. This scenario assumed 95% food grown.

The inedible plant biomass was calculated based on the two BVAD diets. Scenarios 1-3 used the low carbohydrate diet, while scenarios 4 and 5 used the all plants diet. This was calculated by multiplying the ratio of inedible plant biomass over total consumption (including water) times the grown food. The packaged food was assumed to contain 10% inedible biomass (table scraps and food waste). This can be expressed by the following:

$$Inedible = \frac{DietInedible}{DietTotal} \times GrownFood + 0.1 \times PackagedFood$$

TECHNOLOGY READINESS LEVELS

The technology readiness level (TRL) is shown in Figure 2 below. ALS has used the TRL metric to determine where along the development cycle a technology is presently located. The ALS Project has typically focused on developing technologies through TRL 6, but in some cases technologies may need to be flight-tested which increases the TRL metric to a TRL 7.

Figure 2 Technology Readiness Level (TRL) Chart

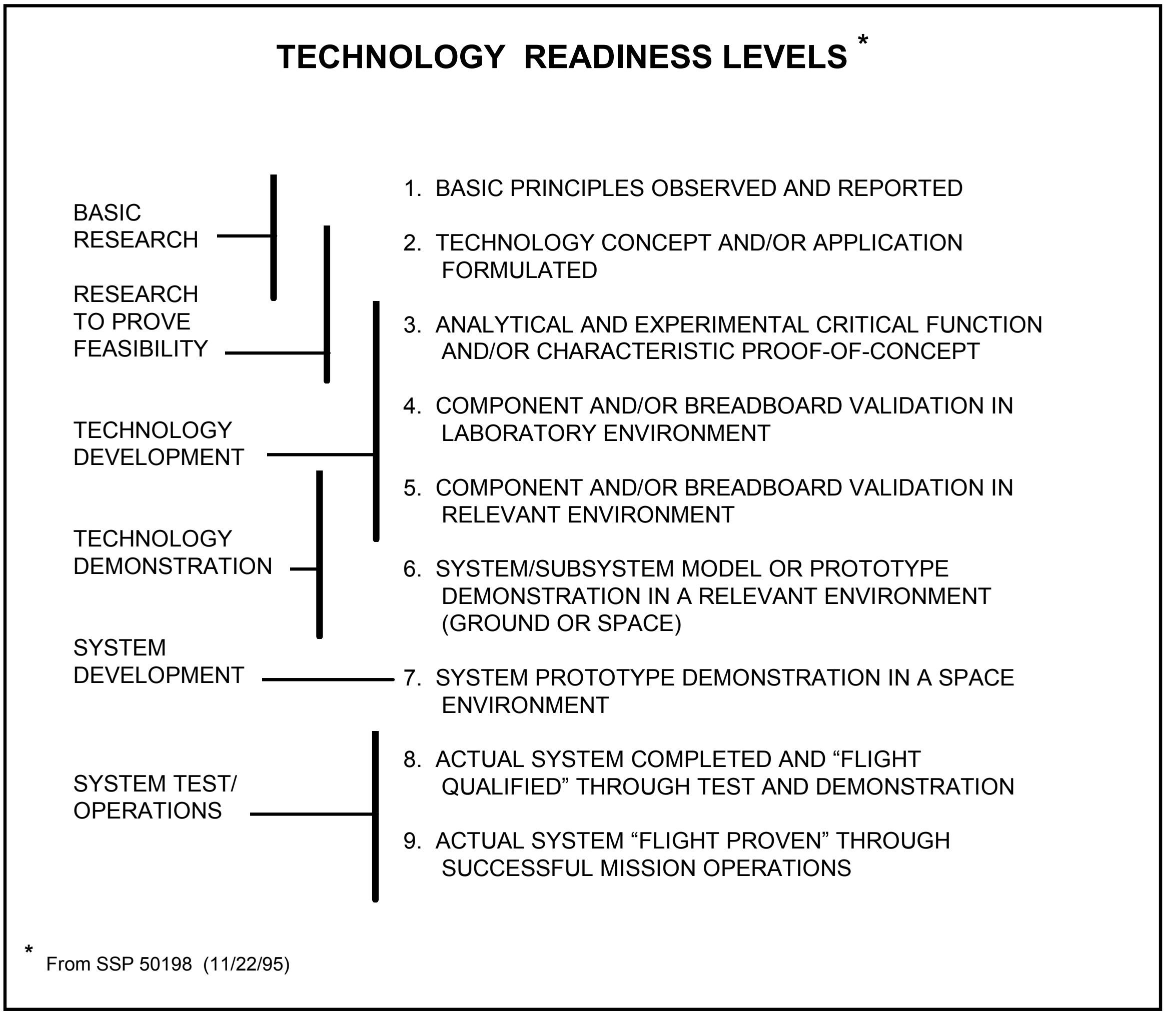


Table 14: Technology Listing

	Technology Name
	Preprocessing Technologies
	Collection, Transport, Vacuum Waste Collection
	Bulk Compaction
	Dry Size Reduction and Particle Size Control
	Drying (Forced Air Thermal Convection, Forced Air, Thermal Vacuum, and Freeze Vacuum)
	Pneumatic Transport - Dry Material
	Screw Conveyor
	Slurry Pumping
	Solid/Liquid Blending; Slurrying (50-95% Water)
	Solid/Solid Blending
	Storage
	Wet Size Reduction and Particle Size Control
	Biological Processing Technologies
	Aerobic Completely Mixed (Slurry) Biological Reactor
	Plant Nutrient Extraction Variant - 7 Day Residence Time (No Curing Stage/Biofilter)
	Plant Nutrient Extraction Variant 21 Day Residence Time
	Fixed-Film Bioreactor
	High-Solids Leach Bed Anaerobic Digestion using SBAC Sequential Batch Anaerobic Composting
	Paper and Biomass to Products
	Single Cell Protein Production and Crop Nutrient Recovery
	Physicochemical Processing Technologies
	Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process
	Batch Incineration
	Continuous Incineration
	High Temperature Gasification
	Electrochemical Oxidation
	Lyophilization (Freeze Drying)
	Magnetically Assisted Gasification (MAG)
	Peroxide Oxidation
	Plasma Arc Thermal Destruction
	Pyrolysis in Sub-Critical Water
	Pyrolysis Processing
	Supercritical Water Oxidation (SCWO)
	Acid Hydrolysis

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

Workshop Charter:
"The goal of this WPRR workshop is to provide input to NASA to develop a research and technology development strategy for WPRR. Candidate waste processing technologies for possible use in future space-based human life support systems are to be assessed at this workshop. Each candidate solid waste processing technology is to be independently assessed in terms of established criteria including mass, power, volume, reliability, use of expendables, technology readiness level, and operational scenarios (e.g. microgravity vs. hypogravity; vehicle vs. planetary surface applications)."

Additional Comments:

1. *Evaluations are also to include an assessment of the technology readiness and its suitability for use in space-based ALS in the context of specific mission scenarios.*

2. *New concepts/technologies that are applicable for solid waste processing are of much interest and an assessment of their features are wanted and requested.*

3. *The waste stream to be processed for this evaluation will be 10.55 kg/day. The makeup of this waste stream is detailed in the waste model document, and is also included in the end of this document. Each technology will be sized to process this entire waste stream, excluding only prohibited waste.*

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE:

FLOW DIAGRAM *(Showing connectivity of components and location of where the various flow streams connect to the components):*

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

PROCESS DATA (NOMINAL & RANGES)
(Empirical Data shall be based on waste model for 6-person crew / Scenario 3)

MAJOR REACTIONS:

SIDE REACTIONS:

RATE EXPRESSION (IF POSSIBLE)

TYPE OF FEED PREPARATION REQUIRED:

FEED RATE (kg/hr):

TYPE CATALYST/ORGANISMS REQUIRED *(show amount required per amount of feed to be processed)*

PROHIBITED WASTES:

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

Table 15: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA (Table 16) THAT IS BASED ON SCENARIO 3 *(Give descriptions and variations).*

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

EQUIPMENT / HARDWARE DATA
Provide values for existing equipment (where available). The scaling should be indicated on the next table

Table 16: MAJOR COMPONENT DATA SHEET
(Indicate crew size applicable for the component)

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1						
2						
3						
4						
5						
1) Indicate if subassembly would need replacement at some other interval.						

Background or reference information:

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

Indicate what the scaling factor would be to scale from actual component to 6 person crew. If component already at that size the factor would be 1.0. In the explanation indicate the basis for scaling (empirical data, other designs, guess). If the unit or design is already sized to 6-person capacity, indicate in the explanation the scaling rationale to other sizes.

Table 17: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]:			Explanation of scaling factor[3]
	Power	Weight	Volume	Power	Weight	Volume	
1							
2							
3							
4							
5							
1) Scaling factor is for sizing components to provide for a larger or smaller system based on flow rate, power, weight and volume. Note: Depending on the process there may be different scaling factors for flow rate, power, weight and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

Background or reference information:

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

EQUIPMENT/HARDWARE DATA
Provide values for existing equipment (where available). The scaling should be indicated on the next table.

Table 18: MINOR COMPONENT/EXPENDABLE DATA SHEET
(Indicate crew size applicable for the component)

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1						
2						
3						
4						
5						
1) Indicate if subassembly would need replacement at some other interval.						

Background or reference information:

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

Indicate what the scaling factor would be to scale from actual component to 6-person crew. If component is already at that size, the factor would be 1.0. In the explanation indicate the basis for scaling (empirical data, other designs, guess). If the unit or design is already sized to 6-person capacity, indicate in the explanation the scaling rationale to other sizes.

Table 19: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]:			Explanation of scaling factor[3]
	Power	Weight	Volume	Power	Weight	Volume	
1							
2							
3							
4							
5							

1) Scaling factor is for sizing components to provide for a larger or smaller system based on flow rate, power, weight and volume. Note: Depending on the process there may be different scaling factors for flow rate, power, weight and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

Background or reference information:

EQUIPMENT/HARDWARE DATA
(Empirical Data to be provided shall be based on waste model for 6-person crew/Scenario 3)

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1,2,4 and 5) THAT MAY AFFECT THE EQUIPMENT / HARDWARE DATA (Tables, 17-20) WHICH IS DIFFERENT FROM SCENARIO 3 *(Give descriptions and variations)*

EXAMPLE – WORKSHOP TECHNOLOGY ASSESSMENT FORM

TECHNOLOGY NAME/TYPE: **Name of technology**

CRITERIA/ISSUES

SPECIFIC CONDITIONS:

Table 20: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks / Comments
Gravity Dependence[2]	
Pretreatment Issues	
Post Treatment Issues	
Safety	
Material	
Environmental Issues	
Reliability	
Integration: Technology Interactions	
Integration: Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY ADVANCES

1) What other alternate technologies are comparable to this one?

2) What other type of technologies would help improve this one?

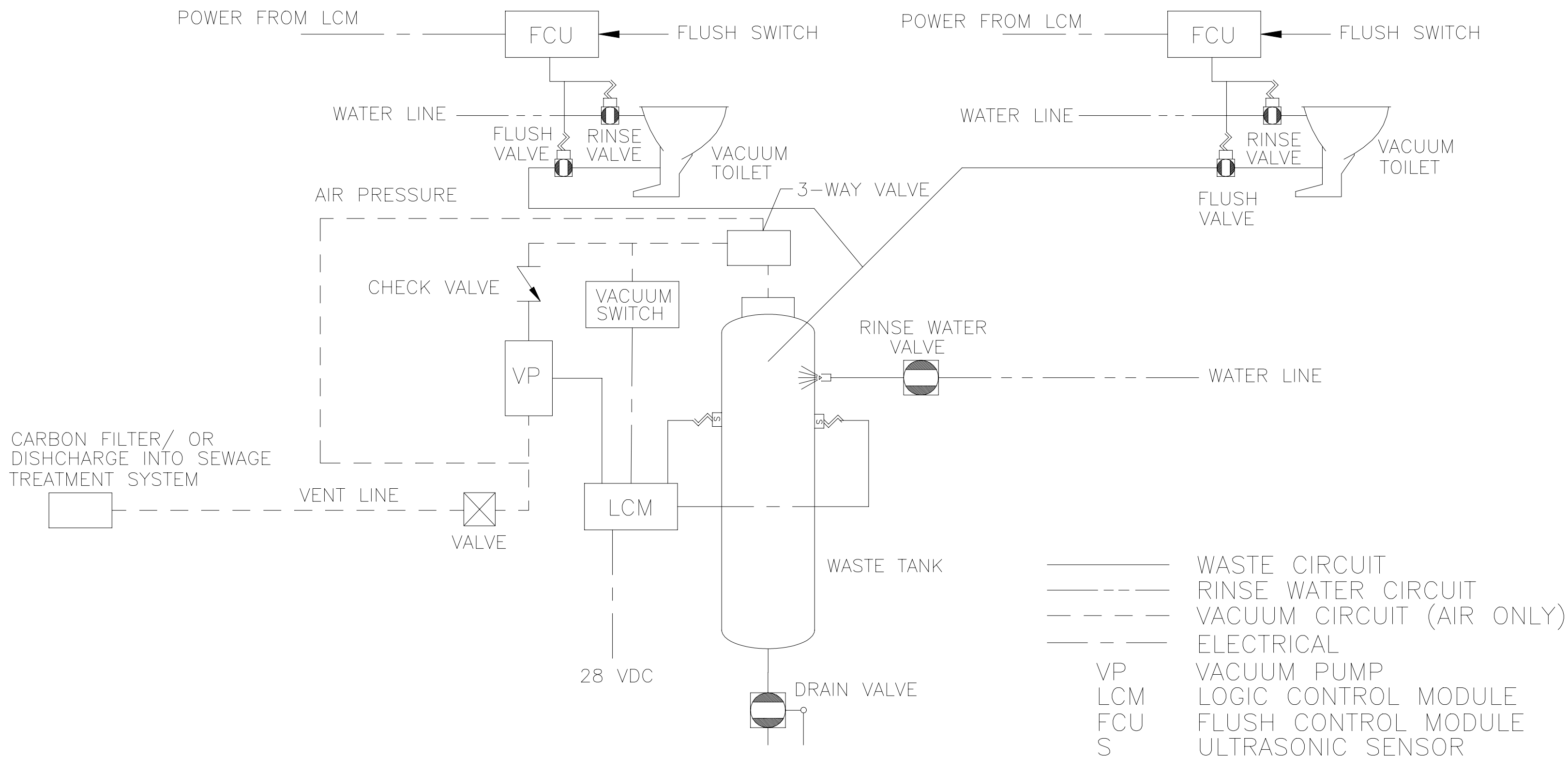
3) What other types of work are currently going on to improve this technology?

TECHNOLOGY ASSESSMENTS: PRE-PROCESSING

This section contains raw data collected for eleven different pre-processing technologies. This raw data represents a subset of pre-processing technologies used terrestrially. Actual pre-processing technologies have been determined to be highly dependent on mission, configuration, and the wastes that are generated. For summarized results on pre- and post-processing technologies please consult Volume I, Section 4.1, of the workshop report.

Collection, Transport, Vacuum Waste Collection

Figure 3: Schematic of Vacuum Waste Collection & Transport Technology



TECHNOLOGY NAME/TYPE: **Collection, Transport, Vacuum Waste Collection**
PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
If the sewage in the holding tank is left in the tank for extended periods of time the sewage will become septic.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
None reported.

TYPE OF FEED PREPARATION REQUIRED:
Anything smaller than 4 cm for wet feed or slurry

FEED RATE (kg/hr):
Liquid flow thru 2-inch diameter pipe with a 4-psi pressure drop

TYPE CATALYST/ORGANISMS REQUIRED:
N/A

PROHIBITED WASTES:
None reported.

PROCESS DATA:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Collection, Transport, Vacuum Waste Collection**

EQUIPMENT/HARDWARE

Table 21: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Vacuum Toilet Assembly or interface valve	7.1	0.065	0.060	?	Flush Valve, Rinse Valve, Flush Control Unit
2	Vacuum Waste Tank Assembly	14.5	0.10	-	-	Ultrasonic Sensor
3	Vacuum Pump	5.45	0.008	0.15	?	Bearings, Diaphragm, Control Valves
4	Drain Valve	2.77	0.0046	-	-	Seal
5	Logic Control Module	0.68	0.0021	0.014	?	

1) Indicate if subassembly would need replacement at some other interval.

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 22: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]:			Explanation of scaling factor[3]
	Power	Weight	Volume	Power	Weight	Volume	
1							No Change
2							No Change up to 15 people
3							No Change up to 15 people
4							No Change
5							No Change

1) Scaling factor is for sizing components to provide for a larger or smaller system based on flow rate, power, weight and volume. Note: Depending on the process there may be different scaling factors for flow rate, power, weight and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Collection, Transport, Vacuum Waste Collection**

Table 23: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Check Valve	0.23	0.00004	N/A	N/A	
2	Water Valve	0.29	0.00006			
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

BACKGROUND/REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA AND DIFFERS FROM SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Collection, Transport, Vacuum Waste Collection**

Table 24: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	May need to be considered for waste/air separation in tank. Also would affect toilet or interface valve.
Pretreatment Issues	N/A
Post Treatment Issues	N/A
Safety	
Material	Approximately 95% of the material is stainless steel. Waste lines should be titanium.
Environmental Issues	
Reliability	Approximately 1 failure will occur per year for the system.
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	The present equipment is level 4 – 5.
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) <u>Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.</u> 3) See Figure 2 for TRL definitions.	

TECHNOLOGY NAME/TYPE: **Collection, Transport, Vacuum Waste Collection**

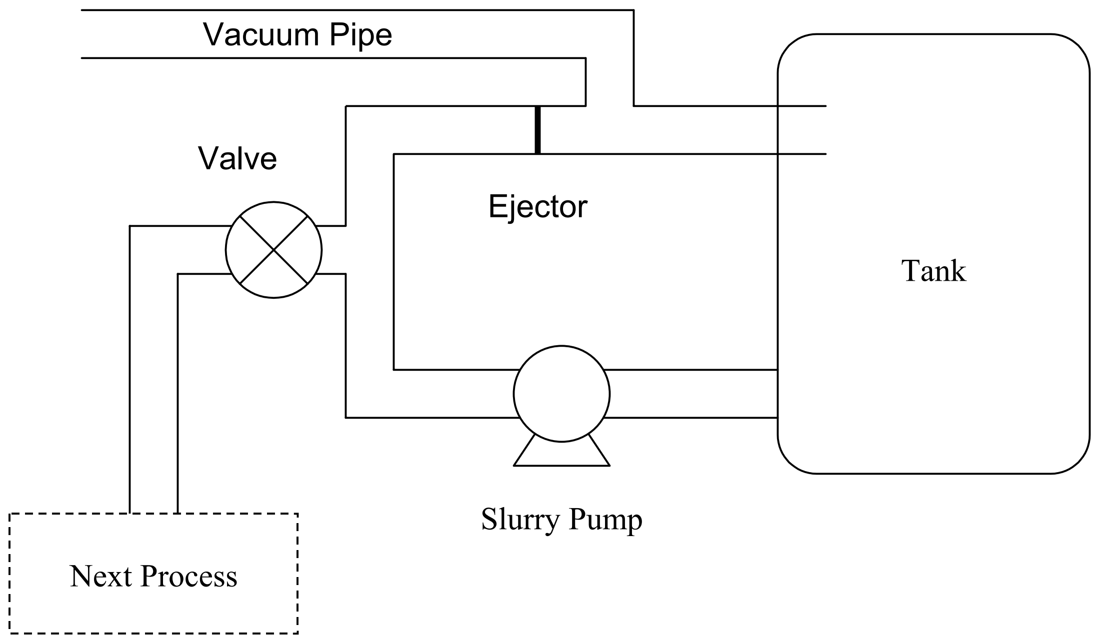
TECHNOLOGY ADVANCES:

1) What other alternate technologies are comparable to this one?
Alternate technology would be to us a liquid ejector to create the delta-P (vacuum) that could also be used to pump the fluid to the next process. An ejector may be better for microgravity conditions (see Figure 4 below).

2) What other type of technologies would help improve this one?

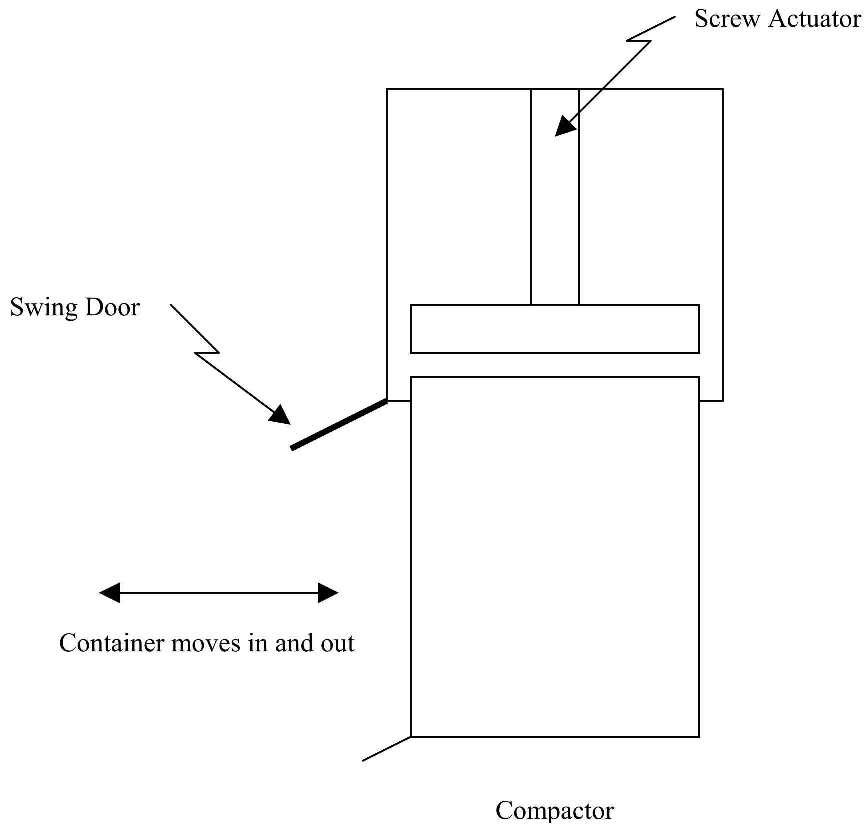
3) What other types of work are currently going on to improve this technology?

Figure 4: Liquid Ejector Technology



Bulk Compaction

Figure 5: Diagram of Bulk Compaction Technology



TECHNOLOGY NAME/TYPE: **Bulk Compaction**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
None reported.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
Not applicable.

TYPE OF FEED PREPARATION REQUIRED:
15 cm is the maximum allowable particle size. No incompressible materials.

FEED RATE (kg/hr):
Batch process (0.1 m^3 per batch)

TYPE CATALYST/ORGANISMS REQUIRED:
None reported.

PROHIBITED WASTES:
None reported.

PROCESS DATA:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3.
None reported.

TECHNOLOGY NAME/TYPE: **Bulk Compaction**

EQUIPMENT/HARDWARE DATA

Table 25: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Linear Screw Actuator (Motor Driven)	4	0.05	0.1	?	
2	Housing	7	0.3	-		
3	Controller	0.1	0.005	0.01		
4	Removable Container	4	Inside of Housing	-		
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 26: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1							Independent of size
2	-	1.0	1.0				
3							Independent of size
4	-	1.0	1.0				

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors

BACKGROUND OR REFERENCE INFORMATION:
Sized for a crew of six (6)

TECHNOLOGY NAME/TYPE: **Bulk Compaction**

EQUIPMENT/HARDWARE DATA

Table 27: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Replacement Bags	0.005 each	0.005 each	--	--	Replacement approximately every five days
2	Safety Switch	0.005	0.005			
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 28: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1		1.0	1.0				
2							Independent of size
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume (see Note and Example on page 2 of Instructions for Scaling Factors). 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors							

BACKGROUND OR REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
No Effect

TECHNOLOGY NAME/TYPE: **Bulk Compaction**

Table 29: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	None
Pretreatment Issues	
Post Treatment Issues	
Safety	Must be closed before operation
Material	
Environmental Issues	
Reliability	
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 4
Estimated Cost of Development to TRL of 5	$200,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 year; $60,000
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

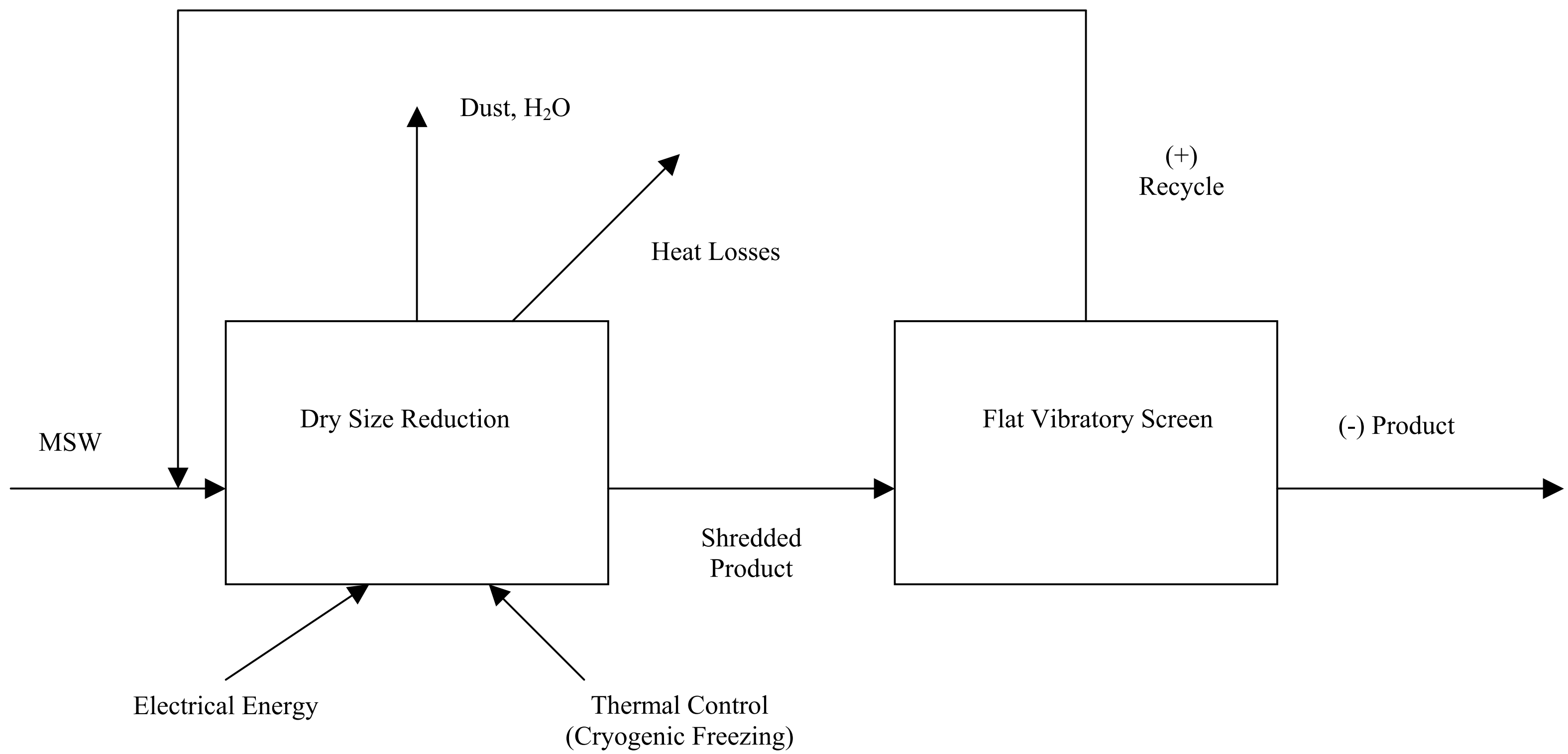
1) What other alternate technologies are comparable to this one?
None reported.

2) What other type of technologies would help improve this one?
None reported.

3) What other types of work are currently going on to improve this technology?
None reported.

Dry Size Reduction and Particle Size Control

Figure 6: Diagram of Dry Size Reduction and Particle Size Control Technology



PRE-PROCESSING TECHNOLOGIES

TECHNOLOGY NAME/TYPE: **Dry Size Reduction and Particle Size Control**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Mechanical processes (e.g., tearing, cutting, abrasion, etc.), conversion of mechanical work to heat, and volatilization of moisture in waste.

SIDE REACTIONS:
Embrittlement (see Figure 6 above)

RATE EXPRESSION (IF POSSIBLE):
The rate expression is a function of flow rate and discharge particle size.

TYPE OF FEED PREPARATION REQUIRED:
Some particle size classification may be needed to remove extremely over-sized materials or stringy materials. May need source separation of certain materials.

FEED RATE (kg/hr):
Unlimited; system size is scaleable

TYPE CATALYST/ORGANISMS REQUIRED (show amount required per amount of feed to be processed):
Water and potentially cooling for embrittlement

PROHIBITED WASTES:
Extremely over-sized and stringy materials, hazardous materials, and some metallic materials

TECHNOLOGY NAME/TYPE: **Dry Size Reduction and Particle Size Control**

Table 30: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
MSW	Maybe H_2O	Dust, unless captured, H_2O, odor	100	298	± 50	101	± 25	5 s	0.1 – 100 s	Discharged particle size: 1 to 100 mm
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
May require some gravitation which would not be present in transit only scenarios (#1), or transit portion of other scenarios.

EQUIPMENT/HARDWARE

Table 31: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Size Reduction Device [2]	50	2	1	TBD	5 years
2	Vibratory Screen [2]	25	1	1	TBD	5 years
1) Indicate if subassembly would need replacement at some other interval. 2) Electric motors are included.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Dry Size Reduction and Particle Size Control**

EQUIPMENT/HARDWARE

Table 32: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0	Exponential	Linear	Linear	Inversely proportional to particle size
2	1.0	1.0	1.0	Exponential	Exponential	Exponential	Inversely proportional to particle size

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 33: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Cutters	5	0.1	N/A	N/A	3/year
2	Liners	15	0.3	N/A	N/A	1/year
3	Screens	5	0.1	N/A	N/A	1/2 years

1) Indicate if subassembly would need replacement at some other interval.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Dry Size Reduction and Particle Size Control**

EQUIPMENT/HARDWARE

Table 34: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0	N/A	Exponential	Exponential	Inversely proportional to particle size
2	1.0	1.0	1.0	N/A	Exponential	Exponential	Inversely proportional to particle size
3	1.0	1.0	1.0	N/A	Exponential	Exponential	Inversely proportional to particle size

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume (see Note and Example on page 2 of Instructions for Scaling Factors).
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors

BACKGROUND OR REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Volume and mass of the size reductions device and energy required is primarily a function of mass throughput and required discharged particle size.

TECHNOLOGY NAME/TYPE: **Dry Size Reduction and Particle Size Control**

Table 35: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Current technology is gravity dependent. Dependence needs to be evaluated.
Pretreatment Issues	Pre-sizing of very large or stringy materials is required. Problematic materials such as hazardous wastes, metals, and plastics should be separated.
Post Treatment Issues	Must be compatible with transport systems.
Safety	Potentially high rotational speeds and also rotational inertia, noise, vibration are health issues. Depending on fineness of size reduction may generate explosive dust.
Material	Normally steel and/or ceramics
Environmental Issues	Fugitive particulate matter control, control of evaporated moisture, noise, vibration, static discharge are environmental issues.
Reliability	Not determined in the microgravity space environment. Preventative maintenance is required. Ground-based reliability is high.
Integration:Technology Interactions	Need to know required discharge particle size distribution. Compatible with downstream transport system.
Integration:Products of Process and their uses	Products include heat, moisture, and dust (recycle to discharged product stream). Properly sized products are to be fed to P/C and Biological Processes.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL for terrestrial systems: 5 – 6; TRL for space based systems: 3
Estimated Cost of Development to TRL of 5	$400,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 year and $500,000
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) <u>Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.</u> 3) See Figure 2 for TRL definitions.	

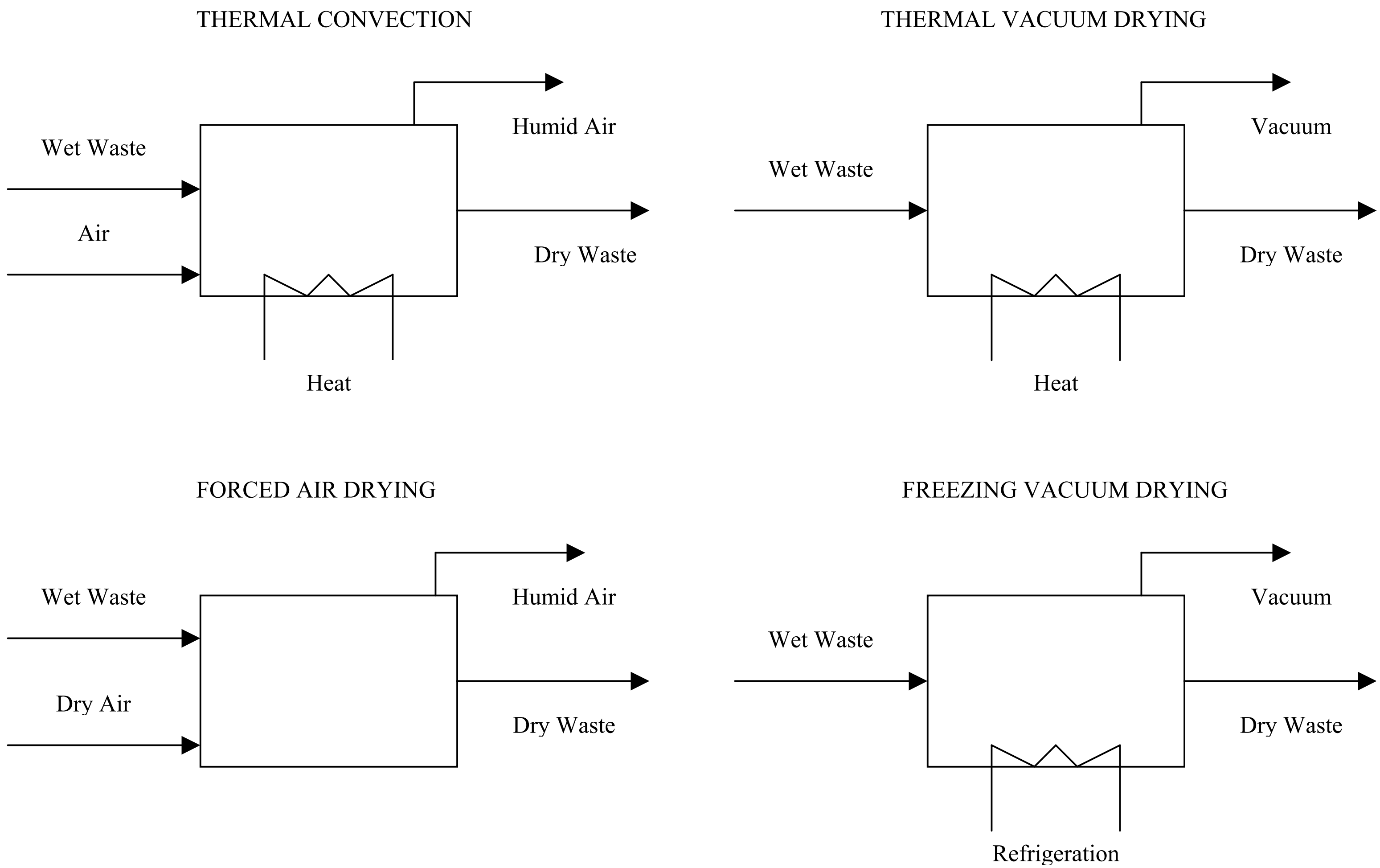
1) What other alternate technologies are comparable to this one? There are a number of size reduction technologies (e.g., high and low speed). There are a number of particle size control technologies (e.g., trommel, disc, etc.).

2) What other type of technologies would help improve this one? Material science and prime mover technologies

3) What other types of work are currently going on to improve this technology? Only basic research to determine mass, volume, and energy requirements for size reduction of space mission solid waste. Status of screening research and development is unknown with respect to spare applications, including gravitational dependency of screening technologies.

Drying (Forced Air Thermal Convection, Forced Air, Thermal Vacuum, and Freeze Vacuum)

Figure 7: Diagram of Drying Technologies



TECHNOLOGY NAME/TYPE**: Drying**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Remove Water: H_2O (liquid) $\Rightarrow$ H_2O (vapor)

SIDE REACTIONS:
Not known. This process may provide some other volatiles.

RATE EXPRESSION (IF POSSIBLE)
Not known.

TYPE OF FEED PREPARATION REQUIRED:
Size reduction for surface area optimization

FEED RATE (kg/hr):
Batch and/or continuous

TYPE CATALYST/ORGANISMS REQUIRED:
Not applicable.

PROHIBITED WASTES:
This depends on dryer temperature. For example, low-density polyethylene (LDPE) melts at 70˚C.

TECHNOLOGY NAME/TYPE: **Drying**

Table 36: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
#3 Waste Stream	0		0	343	323-363	101		TBD		Thermal Air Drying
#3 Waste Stream	0		0		Ambient	101		TBD		Air Dryer
#3 Waste Stream	0		0	343	323-363	$\leq 10^{-3}$		TBD		Thermal Vacuum Drying
#3 Waste Stream	0		0	≤ 273		$\leq 10^{-3}$		TBD		Vacuum Freeze Drying
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
This technology is applicable for all scenarios. Potentially there are microgravity constraints associated with Scenario 1.

EQUIPMENT/HARDWARE

Table 37: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kw)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Thermal Convection Oven	TBD	TBD	TBD	TBD	
2	Air Dryer	TBD	TBD	TBD	TBD	
3	Thermal Vacuum Oven	TBD	TBD	TBD	TBD	
4	Freeze Dryer	TBD	TBD	TBD	TBD	
1) Indicate if subassembly would need replacement at some other interval..						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR: None reported.

BACKGROUND OR REFERENCE INFORMATION: None reported.

TECHNOLOGY NAME/TYPE: **Drying**

Table 38: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Refrigerant	TBD	TBD	TBD	TBD	
2	Blower	TBD	TBD	TBD	TBD	
3	Heating Element	TBD	TBD	TBD	TBD	
1) Indicate if subassembly would need replacement at some other interval.						

MINOR COMPONENT SCALING FACTOR:
None reported.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Equipment modifications for the other missions are not known. In both hypogravity and microgravity, these wastes may require being fixed in position within an oven.

TECHNOLOGY NAME/TYPE: **Drying**

Table 39: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Needs to be determined. Probably need to fix waste material in place (e.g. place in cage).
Pretreatment Issues	Size reduction and mixing maybe required. Fecal material may need to be stabilized.
Post Treatment Issues	Volatiles are possibly an issue.
Safety	Touch temperatures and/or pinch points.
Material	Non-corrosive, non-melting, and non-off-gassing; Stainless Steel is recommended.
Environmental Issues	The freeze dryer may use Freon.
Reliability	Blowers, vacuum system, heating elements, refrigeration system.
Integration:Technology Interactions	Separate out plastics that are incompatible with dryer operating temperature.
Integration:Products of Process and their uses	Dried materials need to be removed (transported) from the drying equipment. Meet some water quality specifications.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 3 to 4
Estimated Cost of Development to TRL of 5	$150,000 – $200, 000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 – 2 years
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

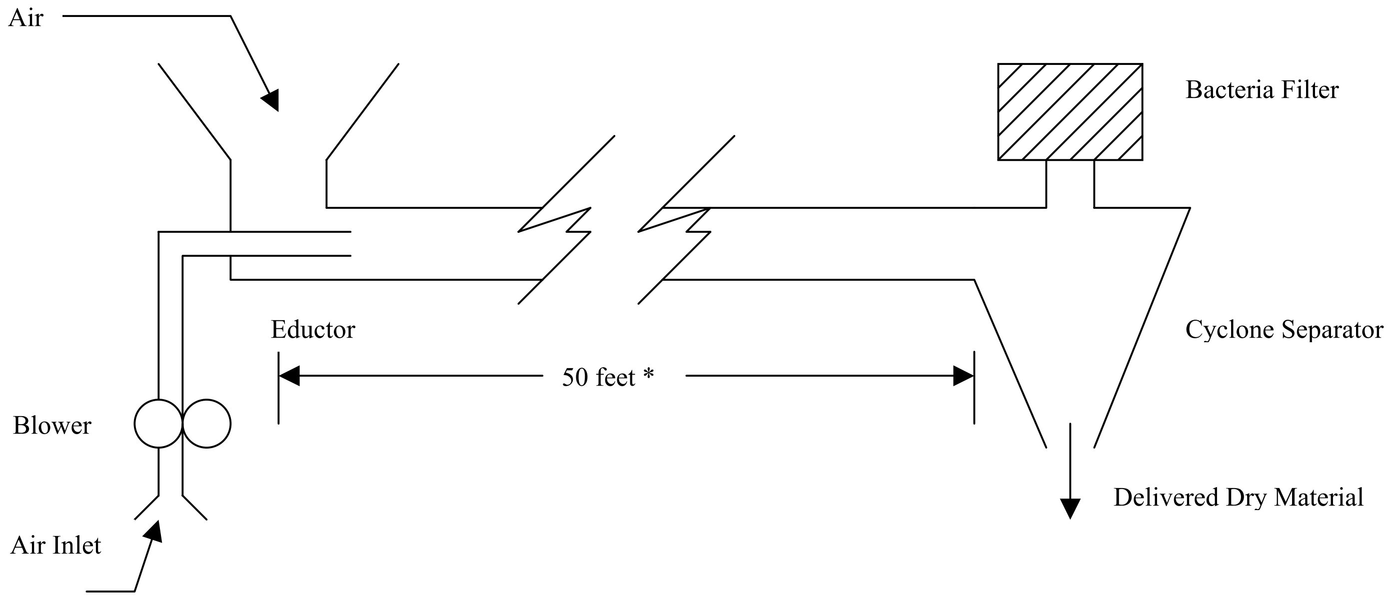
1) What other alternate technologies are comparable to this one?
Composter may be used for volume reduction/drying operating at 55 to 60˚C.

2) What other type of technologies would help improve this one?
Size reduction to improve surface area, and a rotating oven

3) What other types of work are currently going on to improve this technology?
None reported

Pneumatic Transport – Dry Material

Figure 8: Diagram of Pneumatic Transport Technology



* 50-foot transport distance assumed for calculations

TECHNOLOGY NAME/TYPE: **Pneumatic Transport – Dry Material**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
None reported.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
Not applicable.

TYPE OF FEED PREPARATION REQUIRED:
Moisture content of 60% or less, particle size less than 1 cm

FEED RATE (kg/hr):
40 kg/hr with moisture content less than 60%

TYPE CATALYST/ORGANISMS REQUIRED:
Not applicable.

PROHIBITED WASTES:
None reported.

PROCESS DATA
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3: This technology is applicable for all scenarios. Potentially there are microgravity constraints associated with Scenario 1.

TECHNOLOGY NAME/TYPE: **Pneumatic Transport – Dry Material**

EQUIPMENT/HARDWARE

Table 40: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kw)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Blower	5	0.1	0.2	TBD	
2	Cyclone Separator	10	0.1	N/A	N/A	
3	Feed Hopper	10	0.1	N/A	N/A	
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
Cyclone and feed hopper can hold one day worth of material, or approximately 40 kg.

Table 41: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0				
2							

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors

BACKGROUND OR REFERENCE INFORMATION:
Sized for crew of 6.

TECHNOLOGY NAME/TYPE: **Pneumatic Transport – Dry Material**

Table 42: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Bacteria / Particulate filter	TBD	TBD	TBD		
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 43: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0				

BACKGROUND OR REFERENCE INFORMATION: Sized for crew of six.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Extraction from cyclone separator needs to be addressed for Scenario 1.

TECHNOLOGY NAME/TYPE: **Pneumatic Transport – Dry Material**

Table 44: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	See previous page regarding cyclone separator.
Pretreatment Issues	Particle size reduction to < 1 cm.
Post Treatment Issues	
Safety	
Material	Material of construction: metal or plastic.
Environmental Issues	Filtration.
Reliability	
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 3 to 4
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

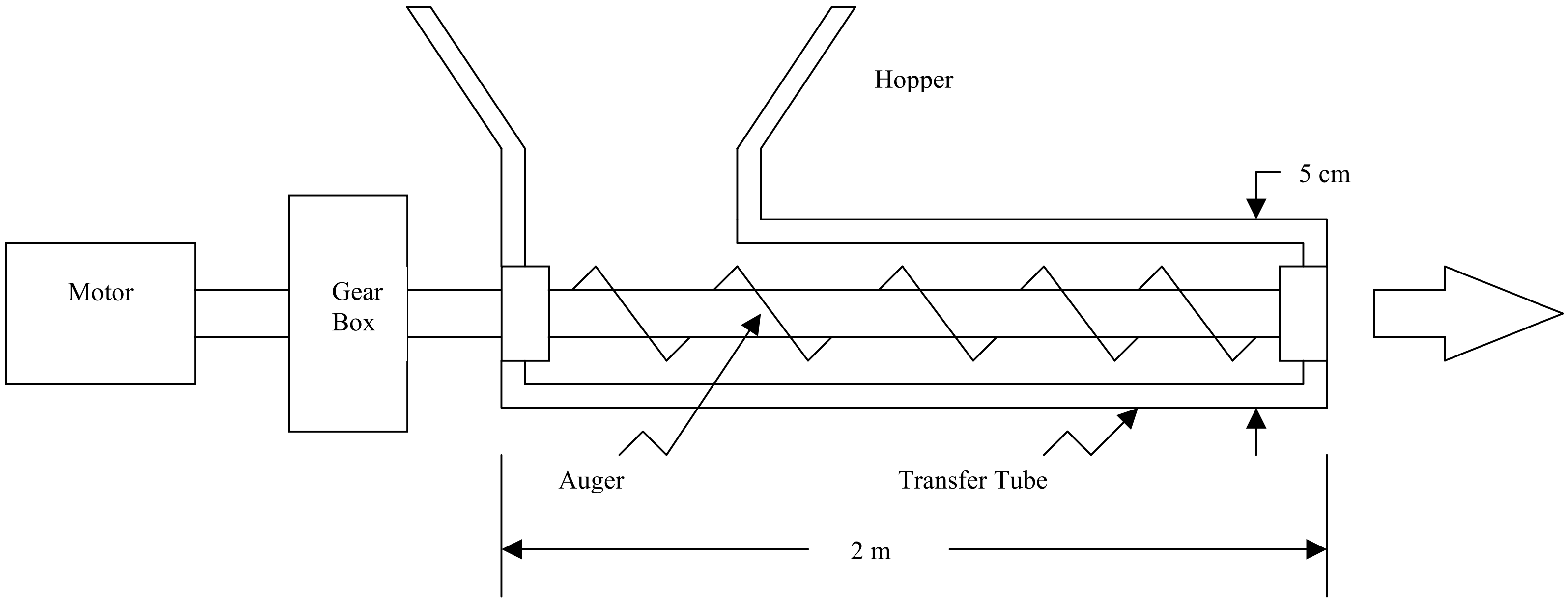
1) What other alternate technologies are comparable to this one?
None reported.

2) What other type of technologies would help improve this one?
None reported.

3) What other types of work are currently going on to improve this technology?
None reported.

Screw Conveyor

Figure 9: Diagram of Screw Conveyor Technology



TECHNOLOGY NAME/TYPE: **Screw Conveyor**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
None reported.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
None reported.

TYPE OF FEED PREPARATION REQUIRED:
Size reduction to less than 1 cm

FEED RATE (kg/hr):
5 to 20 kg/hr (for variable speed)

TYPE CATALYST/ORGANISMS:
None reported.

PROHIBITED WASTES:
None reported.

PROCESS DATA:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Screw Conveyor**

EQUIPMENT/HARDWARE DATA

Table 45: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Motor	5	0.05	0.2	TBD	
2	Gear box	10	0.05	N/A	TBD	
3	Hopper	5	0.1	N/A		
4	Tube and auger	2	0.004	N/A		
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
Hopper can hold one day's worth of material (40 kg).

Table 46: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0				
2							
3							
4							

BACKGROUND OR REFERENCE INFORMATION:
Sized for crew of six.

TECHNOLOGY NAME/TYPE: **Screw Conveyor**

EQUIPMENT/HARDWARE DATA

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

BACKGROUND OR REFERENCE INFORMATION:
Sized for a crew of six (6)

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Hopper feed needs to be addressed for Scenario 1. Also, may require assist (vibratory) for reduced gravity.

TECHNOLOGY NAME/TYPE: **Screw Conveyor**

Table 47: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	See previous page.
Pretreatment Issues	Particle size reduction to less than 1 cm.
Post Treatment Issues	
Safety	
Material	Material of construction: Titanium.
Environmental Issues	Residual material due to intermittent operation may pose problem with odor generation, bacteria, etc.
Reliability	
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 4
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

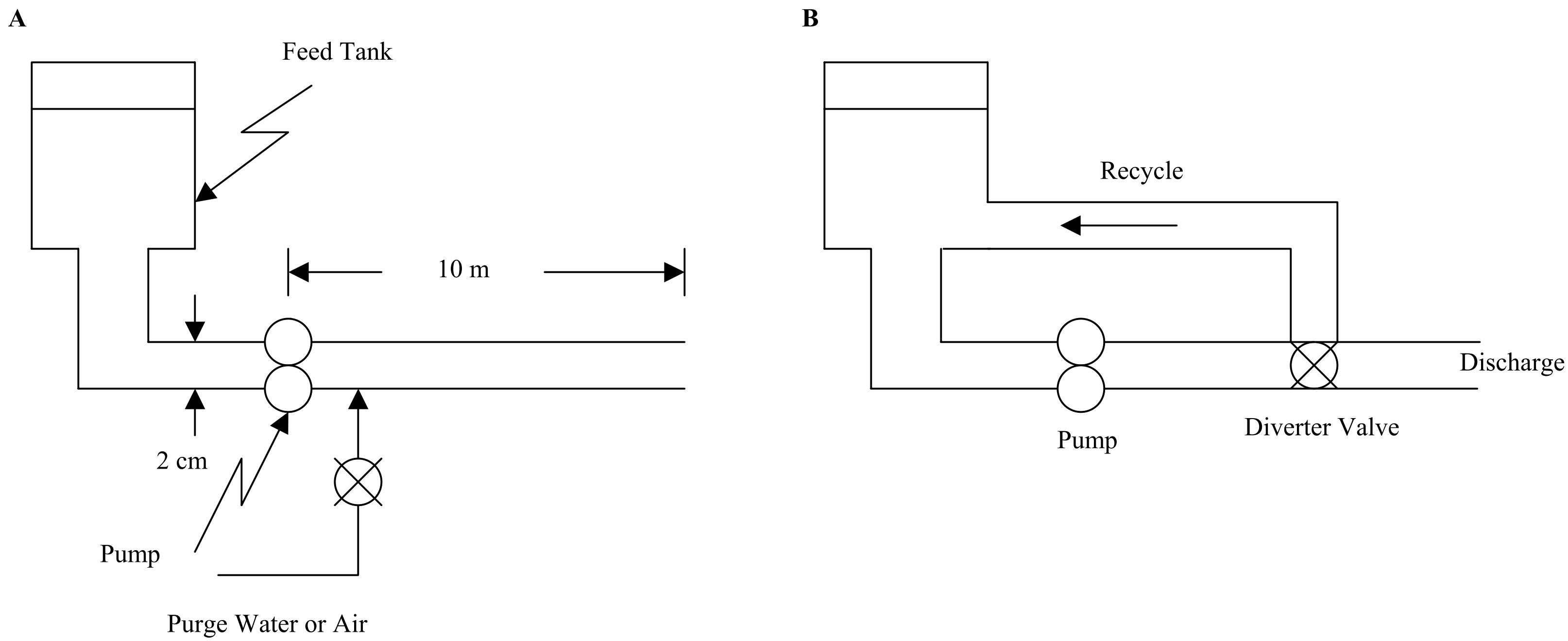
1) What other alternate technologies are comparable to this one?
None Reported.

2) What other type of technologies would help improve this one?
None Reported.

3) What other types of work are currently going on to improve this technology?
None Reported.

Slurry Pumping

Figure 10: Diagram of Slurry Pumping Technology



- System concern over sedimentation of slurry and bio-film and scale build-up. Can purge lines with water or gas (see schematic A).
  OR Continuous recycle with intermittent discharge as needed (see schematic B).
- Concern about rheology at high concentration.

TECHNOLOGY NAME/TYPE: **Slurry Pumping**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
None reported.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
Not applicable.

TYPE OF FEED PREPARATION REQUIRED:
Particle sizes less than 1 mm and diluted to less than 5% solids

FEED RATE (kg/hr):
100 kg/hr

TYPE CATALYST/ORGANISMS REQUIRED (show amount required per amount of feed to be processed):
None reported.

PROHIBITED WASTES:
None reported.

PROCESS DATA:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Slurry Pumping**

EQUIPMENT/HARDWARE DATA

Table 48: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Pump	5	0.1	0.2	?	
2	Feed Tank	20	0.4	N/A		
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
Feed tank will hold half of total material. The total is 790 kg of dilute slurry.

Table 49: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1	1	1				
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND OR REFERENCE INFORMATION:
Sized for a crew of six people

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Feed from supply tank would be a bellows tank for Scenario 1.

TECHNOLOGY NAME/TYPE: **Slurry Pumping**

Table 50: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	See previous page.
Pretreatment Issues	Size reduction to less than 1 mm and with dilution to less than 5% solids
Post Treatment Issues	
Safety	
Material	Titanium
Environmental Issues	
Reliability	
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 4
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	See flow diagram and associated comments.
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

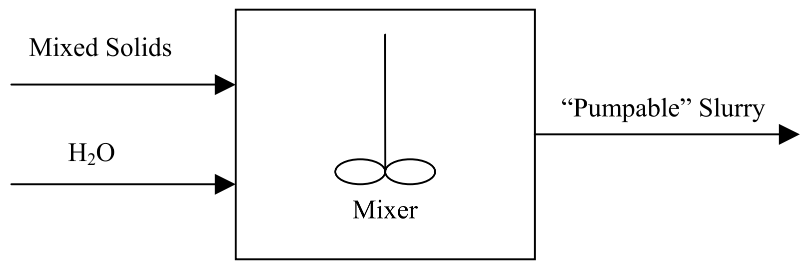
1) What other alternate technologies are comparable to this one?
None reported.

2) What other type of technologies would help improve this one?
None reported.

3) What other types of work are currently going on to improve this technology?
None reported.

Solid/Liquid Blending: Slurrying (50-95% Water)

Figure 11: Diagram of Solid/Liquid Blending (Slurrying) Technology



TECHNOLOGY NAME/TYPE**: Solid/Liquid Blending: Slurrying (50-95% Water)**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
None reported.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
None reported.

TYPE OF FEED PREPARATION REQUIRED:
Size reduction

FEED RATE (kg/hr):
To be determined; continuous and/or batch

TYPE CATALYST/ORGANISMS REQUIRED:
None reported.

PROHIBITED WASTES:
Prohibited wastes are glass and metals.

TECHNOLOGY NAME/TYPE**: Solid/Liquid Blending: Slurrying (50-95% Water)**

Table 51: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
	9:1	1:1	0	Ambient		Ambient		Less than 1 hour		Pumpable Slurry
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
As is, this technology would not be appropriate for Scenario 1. This technology is fine for Scenarios 2 to 5.

EQUIPMENT/HARDWARE DATA

Table 52: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Blender/Homogenizer	TBD	TBD	TBD	TBD	Motor, blades, valves, seals, bearings
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 53: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	TBD	TBD	TBD	TBD	TBD	TBD	
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND OR REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Solid/Liquid Blending: Slurrying (50-95% Water)**

EQUIPMENT/HARDWARE DATA

Table 54: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Blades/Agitator	TBD	TBD	TBD	TBD	
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 55: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	TBD	TBD	TBD	TBD	TBD	TBD	
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND OR REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Not applicable to Scenario 1

TECHNOLOGY NAME/TYPE**: Solid/Liquid Blending: Slurrying (50-95% Water)**

Table 56: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Yes, gravity dependent. Dependence in hypogravity and microgravity must be determined.
Pretreatment Issues	Size reduction
Post Treatment Issues	The product stream may be pumped.
Safety	Rotating equipment, containment
Material	Non-corrosive, able to withstand high heat associated with sterilization, and easily cleaned
Environmental Issues	None
Reliability	Motor, blades, valve, bearings, and seals
Integration:Technology Interactions	Transport in to and out of mixer
Integration:Products of Process and their uses	Not applicable
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 2 – 3
Estimated Cost of Development to TRL of 5	$150,000 to $200,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 – 2 years
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

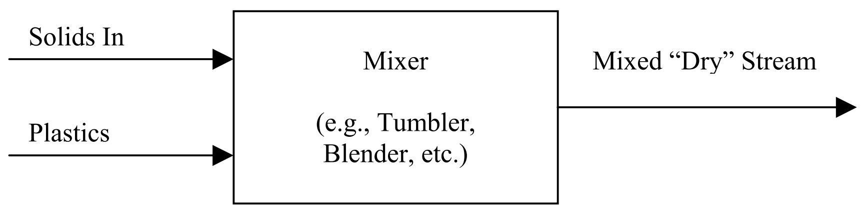
1) What other alternate technologies are comparable to this one?
A macerator pump. This process needs water.

2) What other type of technologies would help improve this one?
Improved bearings and seals

3) What other types of work are currently going on to improve this technology?
None reported.

Solid/Solid Blending

Figure 12: Diagram of Solid/Solid Blending Technology



TECHNOLOGY NAME/TYPE: **Solid/Solid Blending**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
None reported.

SIDE REACTIONS:
None reported.

RATE EXPRESSION (IF POSSIBLE):
Not applicable.

TYPE OF FEED PREPARATION REQUIRED:
Size reduced.

FEED RATE (kg/hr):
Batch and/or continuous

TYPE CATALYST/ORGANISMS REQUIRED:
None reported.

PROHIBITED WASTES:
Glass and metals are prohibited wastes.

TECHNOLOGY NAME/TYPE: **Solid/Solid Blending**

Table 57: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
	0	1	0	Ambient		Ambient		Less than 1 hour		
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
This equipment will not be needed for Scenario 1.

EQUIPMENT/HARDWARE DATA

Table 58: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Homogenizer	TBD	TBD	TBD	TBD	Motor, seals, and bearings
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR:
None reported.

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

TECHNOLOGY NAME/TYPE: **Solid/Solid Blending**

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3: Microgravity could cause problems with this process. Issues need to be determined, e.g., particulate, mixing, etc.

Table 59: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Yes, this technology is gravity dependent. Its needs for microgravity and hypogravity need to be determined.
Pretreatment Issues	Size of particles reduced
Post Treatment Issues	Particulates in case of dried wastes
Safety	Rotating machines, dust formation from dry materials, containment
Material	Non-corrosive and easily cleaned
Environmental Issues	
Reliability	Motor, seals, and bearings
Integration:Technology Interactions	Transport in to and out of the processor
Integration:Products of Process and their uses	Not applicable
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 2 – 3
Estimated Cost of Development to TRL of 5	$150,000 to $250,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 – 2 years

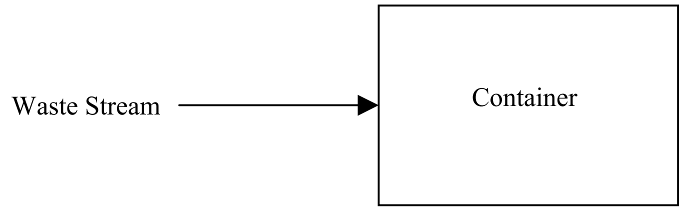
1) What other alternate technologies are comparable to this one?
None reported.

2) What other type of technologies would help improve this one?
Improved bearings and seals

3) What other types of work are currently going on to improve this technology?
None reported.

Storage

Figure 13: Storage Flow Diagram



TECHNOLOGY NAME/TYPE: **Storage**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Not applicable

SIDE REACTIONS:
Off-gassing (volatiles and H_2O) and microbial growth

RATE EXPRESSION (IF POSSIBLE):
Not applicable

TYPE OF FEED PREPARATION REQUIRED:
1) Biological/Chemical Stabilization
2) Pre-packaging (e.g., plastic bags)

FEED RATE (kg/hr):
Not applicable

TYPE CATALYST/ORGANISMS REQUIRED:
Not applicable

PROHIBITED WASTES:
None, if properly designed.

PROCESS DATA
None reported.

TECHNOLOGY NAME/TYPE: **Storage**

EQUIPMENT/HARDWARE DATA

Table 60: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Storage Container	<50	0.01-2.0	N/A	N/A	5 years
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR:
None reported.

Table 61: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Lid	1-10	0.1	N/A	N/A	5 years
2	Hinges	Negligible	Negligible	N/A	N/A	5 years
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION:
None reported

MINOR COMPONENT SCALING FACTOR
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Structural requirements are different between micro- and hypogravity.

TECHNOLOGY NAME/TYPE: **Storage**

Table 62: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	While construction may differ due to gravity issues, this technology applies in any gravity environment.
Pretreatment Issues	Wastes may require to be prepackaged.
Post Treatment Issues	Cleaning of used container
Safety	
Material	Steel and plastic
Environmental Issues	Ingress/egress of volatiles in and out of storage unit
Reliability	High
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 9
Estimated Cost of Development to TRL of 5	N/A
Estimated Time & Cost to Manufacture a Unit to TRL of 5	N/A
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

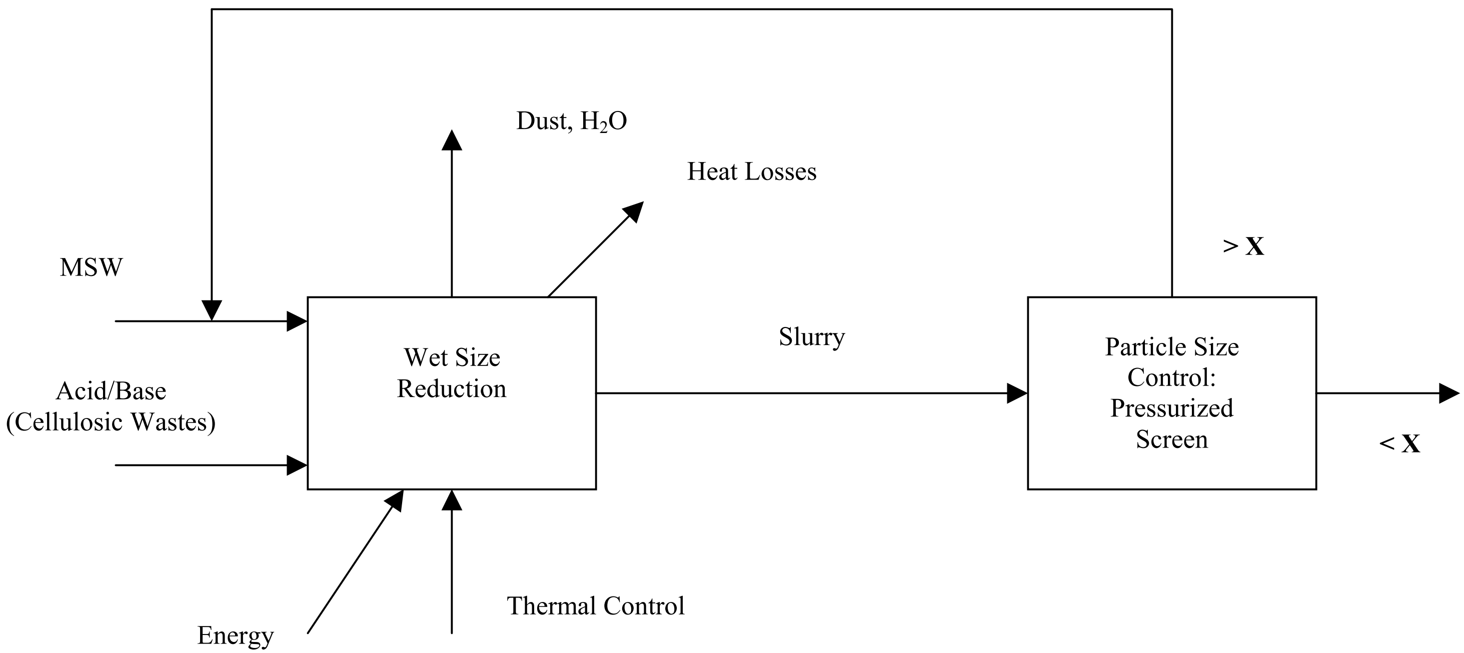
1) What other alternate technologies are comparable to this one?
None reported.

2) What other type of technologies would help improve this one?
Odor control technologies.

3) What other types of work are currently going on to improve this technology?
None reported.

Wet Size Reduction and Particle Size Control

Figure 14: Diagram of Wet Size Reduction and Particle Size Control



Note: X denotes the acceptable particle size of 0.01 cm

TECHNOLOGY NAME/TYPE: **Wet Size Reduction and Particle Size Control**

MAJOR REACTIONS:
Mechanical processes (e.g., tearing, cutting, abrasion, etc.), conversion of mechanical work to heat, and volatilization of moisture in waste. Potential chemical reactions to aid in size reduction (i.e., acids or bases to assist hydrolysis reactions).

SIDE REACTIONS:
See Figure 14 above. Charring.

RATE EXPRESSION (IF POSSIBLE):
The rate expression is a function of flow rate and particle size reduction. It is also a function of temperature for the hydrolysis reactions.

TYPE OF FEED PREPARATION REQUIRED:
Some particle size classification may be needed to remove extremely over-sized materials or stringy materials. May need source separation for specific materials.

FEED RATE (kg/hr):
Unlimited. System size is scalable.

TYPE CATALYST/ORGANISMS REQUIRED:
Water, acid or base for hydrolysis if used.

PROHIBITED WASTES:
Prohibited wastes include extremely over-sized and stringy materials, hazardous materials, and some metals.

TECHNOLOGY NAME/TYPE: **Wet Size Reduction and Particle Size Control**

Table 63: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
MSW	Maybe H_2O	Volatiles, Odor, H_2O	100	298	279 – 348	101	$\pm$ 25	10 min	5 – 15 min	Discharged particle size: 0.01 mm to 100 mm
Cellulose Feedstock	Acid/0.2% to 1.2% by weight	Volatiles	100	453	423 – 523	690	$\pm$ 50	20 min	3 – 120 min	Discharge is a pumpable slurry with particles less than 0.2 mm
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
The effect of entrained gas in microgravity must be considered with respect to particle size separation.

EQUIPMENT/HARDWARE DATA

Table 64: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Size Reduction [2]	75	2.5	2 w/o heat; 5 w/ heat	90%	5 years
2	Screen [2]	25	1	1	90%	5 years
3	Size Reduction Hydrolysis [2]	100	1	10	90%	2 years
1) Indicate if subassembly would need replacement at some other interval. 2) Includes an electric motor.						

BACKGROUND OR REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Wet Size Reduction and Particle Size Control**

EQUIPMENT/HARDWARE DATA

Table 65: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0	Exponential	Linear	Linear	Inversely proportional to particle size
2	1.0	1.0	1.0	Exponential	Exponential	Exponential	Inversely proportional to particle size
3	1.0	1.0	1.0	Linear	Linear	Linear	

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

Table 66: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Cutters	7.5	0.15	N/A	N/A	3/year
2	Liners	20.0	0.4	N/A	N/A	1/year
3	Screens	5	0.1	N/A	N/A	1/2 year

1) Indicate if subassembly would need replacement at some other interval.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Wet Size Reduction and Particle Size Control**

Table 67: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1.0	1.0	1.0	n/a	Exponential	Exponential	Inversely proportional to particle size
2	1.0	1.0	1.0	n/a	Exponential	Exponential	Inversely proportional to particle size
3	1.0	1.0	1.0	n/a	Exponential	Exponential	Inversely proportional to particle size

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume (see Note and Example on page 2 of Instructions for Scaling Factors).
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Volume and mass of the size reductions device and energy required is primarily a function of mass throughput and required discharged particle size.

TECHNOLOGY NAME/TYPE: **Wet Size Reduction and Particle Size Control**

CRITERIA/ISSUES

SPECIFIC CONDITIONS:

Table 68: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Wet particle size reduction is gravity independent, while current particle size control is gravity dependent.
Pretreatment Issues	Pre-sizing of very large or stringy materials is required. Problematic materials such as hazardous wastes, metals, and plastics should be separated.
Post Treatment Issues	Must be compatible with transport systems.
Safety	High rotational speeds and inertial energy, high pressures (for acid hydrolysis), and health issues related to microbial contamination are safety issues.
Material	Normally steel and/or ceramics
Environmental Issues	Noise and vibration
Reliability	Ground based systems are reliable, while space based systems are unknown
Integration:Technology Interactions	Need to know particle size requirements and rheology for pumpable slurries.
Integration:Products of Process and their uses	Slurry to be fed to physicochemical or biological processes
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	Basic system: terrestrial 5 –6; space 3, cellulose subsystem 2 : $70,000
Estimated Cost of Development to TRL of 5	$400,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 year and $500,000
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY NAME/TYPE: **Wet Size Reduction and Particle Size Control**

TECHNOLOGY ADVANCES:

1) What other alternate technologies are comparable to this one?
There are a number of size reduction technology alternatives, e.g., high speed and low speed. There are a number of particle size control technologies, e.g., trommel, disc, etc. Enzymatic degradation of biomass to break down cellulose and/or lignin sufficiently to allow the formation of high solids, loaded slurries.

2) What other type of technologies would help improve this one?
Material science and prime mover technologies. Enzymatic systems may improve cellulose breakdown by reducing temperature and pressure, and increasing processing rate. Developments of thermally stable enzymes for the breakdown of cellulose and lignin may permit much lower operating temperatures and pressures, and higher process rates. Such developments will result in much higher volumetric and energy efficiency.

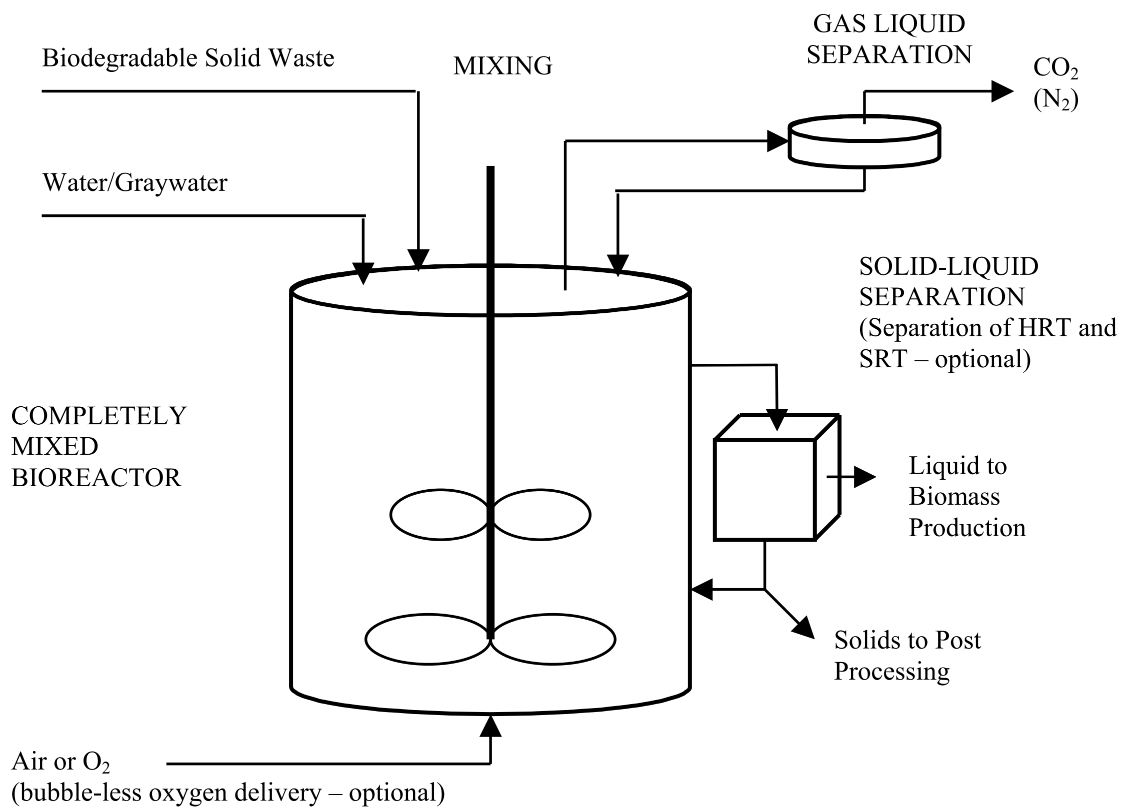
3) What other types of work are currently going on to improve this technology?
Only basic research to determine mass, volume, and energy requirements for size reduction for space mission solid waste. Status of screening research and development in unknown with respect to space applications including gravitational dependency of screening technologies. There are some efforts to utilize biomass for the production of commercially important products. A prime example of a potential commercial application is a U.S. Department of Energy (DOE)/New York State Energy Resource Development Authority (NYSERDA) funded industrial collaboration with Biofine Industries to design and build a 1 ton per day pilot plant to convert paper mill sludge into levulinic acid. A continuous process for producing levulinic acid from carbohydrate-containing materials has been patented by Biofine Incorporated and invented by Fitzpatrick (U.S. Patent # 5,608,105). According to the patent, a carbohydrate-containing material is supplied continuously to a first reactor and hydrolyzed at between 210-230°C for 13-25 seconds in the presence of between 1-5 wt% mineral acid. The first hydrolysis step produces hydroxymethylfurfural, which is removed continuously and supplied continuously to a second reactor. In the second reactor, the hydroxymethylfurfural is hydrolyzed further between 195-215°C for between 15-30 minutes to produce levulinic acid. 60-70% of the theoretical yield is obtained based on the hexose content of the original feedstock. Short-term industrial uses for levulinic acid conversion include diphenolic acid for plastic intermediates, pyrrolidines/pyrroldinones as ‘green’ pesticides. Longer-term industrial uses include conversion to 1,4 butanediol, γ-butyrolactone, and tetrahydrofuran for plastics and nylons. In addition, the gasoline additive methyl tetrahydrofuran can be manufactured.

TECHNOLOGY ASSESSMENTS: BIOLOGICAL PROCESSING

This section contains raw data collected on seven different biological processing technologies. What technologies are needed will depend on requirements, many of which have not been defined to this point. Waste processing requirements have been shown to be highly dependent on mission, configuration, and the types of wastes that are generated. For summarized results on biological technologies please consult Volume I, Section 4.2, of the workshop report.

Aerobic Completely Mixed (Slurry) Biological Reactor

Figure 15: Diagram of Aerobic Completely Mixed (Slurry) Biological Reactor



TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

PROCESS DATA (NOMINAL & RANGES):

MAJOR REACTIONS:
Aerobic microbial oxidation of biodegradable organics, including soluble and particulate components from crop residues, inedible biomass, paper waste, trash, food remains, and human solid wastes (feces, urine solids, shower/handwash solids, and sweat).

Soluble organics can be taken as primarily carbohydrates. Using this assumption the balanced stoichiometric reaction (assuming no net accumulation of microbial biomass) is:
$CH_2O + O_2 \Rightarrow CO_2 + H_2O$

Particulate organics can be taken as primarily carbohydrates (high molecular weight polysaccharides, cellulose, hemicellulose). Using this assumption, the balanced stoichiometric reaction (assuming no net accumulation of microbial biomass) is:
$CH_2O + O_2 \Rightarrow CO_2 + H_2O$

The additional step involved in degradation of particulate organics involves depolymerization, usually carried out through hydrolysis reactions. The hydrolysis reactions are not oxidation/reduction reactions so their stoichiometry is not important here. The difference between the reactions for soluble and particulate organics can be accounted for kinetically as demonstrated in the rate equations.

ADDITIONAL REACTIONS:
These potentially favorable reactions can occur in the reactor. The extent and rate of these reactions depend on environmental conditions (e.g., temperature, dissolved oxygen, pH) and operating parameters (e.g., solids residence time, hydraulic residence time).

Microbial oxidation of ammonia by autotrophic nitrifiers, i.e., nitrification (ammonia is released from the degradation of proteins, amino acids, and other nitrogen containing organic compounds):
$NH_4^+ + 2\ O_2 \Rightarrow NO_3^- + H_2O + 2\ H^+$

The actual reaction is carried out in two steps by different classes of nitrifiers. Both steps are carried out with oxygen as the terminal electron acceptor (aerobic reaction). Ammonia oxidizers oxidize ammonia to nitrite; nitrite oxidizers oxidize nitrite to nitrate.
$NH_4^+ + 1.5\ O_2 \Rightarrow NO_2^- + H_2O + 2\ H^+$
$NO_2^- + 0.5\ O_2 \Rightarrow NO_3^-$

Microbial oxidation of organic compounds with nitrate as the terminal electron acceptor, i.e., heterotrophic denitrification:
$CH_2O + 0.8\ NO_3^- + 0.8\ H^+ \Rightarrow CO_2 + 1.4\ H_2O + 0.4\ N_2$

SIDE REACTIONS:
Potential undesirable side reactions include the formation of NO and N_2O as gaseous intermediates in the formation of N_2 during denitrification. [Note: The work at Kennedy Space Center (KSC) has not reported the production of NO or N_2O for this process, but the literature on heterotrophic denitrification contains many reports in which these compounds have been observed.]

RATE EXPRESSION (IF POSSIBLE):
Descriptive information concerning reaction rates:
Soluble organic compounds/monosaccharides and some oligo- and polysaccharides, can be completely biodegraded within 3 to 6 hours retention time. Other polysaccharides, cellulose and hemicelluloses, can be ca. 50% biodegraded with a hydraulic retention time of 8 to 10 days. Very long retention times of 24 to 48 days will give 60 to 80% bioconversion of these polymers to CO_2 and H_2O.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

Reaction rate expression and kinetic parameter estimates:
While more complex rate expressions can be formulated, the current level of data analysis does not allow for their calibration. The following simple model should be useful for system level analysis until such time as additional data analysis can be performed. This kinetic model and the kinetic parameter estimates for it were developed by Dr. Robert M. Cowan using data from the KSC ALS Breadboard work on treatment of hydroponically grown wheat straw.

The references used included:
Strayer, R. F., Finger, B. W., and Alazraki, M. P. (1997) "Effects of bioreactor retention time on aerobic microbial decomposition of CELSS crop residues." *Adv. Space Res.* **20**:2023-2028.
Discussions with the authors
Additional data (not available at the workshop during development of this model) is available in:
Strayer, R. F., *et al.* (2000 – In Press) *Bioprocess Technology*.

The model is written as:

$$\frac{dS_S}{dt} = k_S S_S = k_S\left(S_T - S_I\right)$$

$$\frac{dX_S}{dt} = k_S X_S = k_S\left(X_T - X_I\right)$$

where:
- S_S = Biodegradable soluble carbon
- X_S = Biodegradable particulate carbon
- S_T = Total soluble carbon
- S_I = Inert soluble carbon (not biodegradable)
- X_T = Total particulate carbon
- X_I = Inert particulate carbon (not biodegradable)
- k_S = rate coefficient for biodegradation of soluble carbon
- k_X = rate coefficient for biodegradation of particulate carbon

Reasonable estimates for the parameter values are:
- k_S = 6 to 18 day^{-1}
- k_X = 0.2 day^{-1}

These kinetic parameters will work well for the Scenario 3 waste stream that will have a composition (based on inedible biomass and paper waste):
- S_T = Soluble carbon = 25% total carbon
- X_T = Particulate carbon = 70% of total carbon
- S_S = Biodegradable soluble carbon = 80% of the soluble carbon, 20% of soluble carbon
- X_S = Biodegradable particulate carbon = 73% of particulate carbon, 55% of total carbon

TYPE OF FEED PREPARATION REQUIRED:
Drying of crop residues: oven-dry at 70^{o}C to constant weight OR freeze-drying (usually 2 weeks)
MAY be able to take FRESH chopped crop residues - (to be determined)
Milling of crop residues: to 2 mm diameter
MAY be able to take CHOPPED (2 cm length) crop residues

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

PROCESS DATA

Table 69: Requirements Given to Pre-Processing Team

Technology Need	Details	Additional comments
Separation	Keep waste streams separate to avoid placing plastic, metal, ceramics (non-biodegradable) materials from entering the process	Separation is only required to the extent that it keeps the undesired materials out of the influent of the appropriate biological processor.
Adjust Moisture Content	Input to the process should have a moisture content of between 40 to 70% (up to 85% for anaerobic)	This can be adjusted by mixing relatively dry materials with those having high moisture content so it is difficult to specify. There will likely need to be drying operations.
Chopping /Shredding (particle size reduction)	Large particle size solid waste should be reduced to a particle size range of 0.5 to 5 cm. (The presence of fines in this material is O.K.)	Plant biomass, paper, etc., should be shredded.
Mixing /Blending	Small particle size materials, sludge, slurries, pastes (e.g., feces) and the other particulate materials must be blended together (potentially with recycled compost) before input to the process	Mixing blending must be done in a way as to maintain a highly porous material that air will flow through. (30 to 40% porosity is a good range.)
Transportation to Process		
Frequency of Addition (batch /continuous)	Process can be run either way.	It is likely that there will be requirements for storage of inputs and/or outputs. Stored inputs will likely need to be stabilized by drying.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

PROCESS DATA (NOMINAL & RANGES)

FEED RATE (kg/hr): 8.13 kg/day
This includes all biodegradable solid waste. Specifics on composition and rate are:

Table 70: Composition of biodegradable portion of solid waste (Scenario 3)

Solid Waste Stream Components	Dry Mass (kg/day)	Fraction Ash	Fraction Carbon	Fraction Nitrogen	Ash (kg/day)	Carbon (kg/day)	Nitrogen (kg/day)
Feces	0.180	0.430	0.420	0.083	0.077	0.076	0.015
Shower /Sweat Solids	0.180	0.500	0.250	0.040	0.090	0.045	0.007
Inedible Plant Biomass	5.450	0.150	0.450	0.050	0.818	2.453	0.273
Trash	0.556	0.020	0.450	0.005	0.011	0.250	0.003
Packaging (food remains)	0.600	0.050	0.440	0.040	0.030	0.264	0.024
Paper Waste	1.164	0.020	0.450	0.005	0.023	0.524	0.006
Total	**8.130**				**1.049**	**3.611**	**0.327**
Urine Solids	0.360	0.560	0.176	0.217	0.202	0.063	0.078

Note that urine solids should be excluded unless post processing is used to remove sodium (and chloride) from the water before it is returned to plants as a nutrient solution.

TYPE CATALYST/ORGANISMS REQUIRED:
No catalyst required. Microbial inoculum probably not required (self-inoculated from crop residues and human solid wastes).

PROHIBITED WASTES:
Anything not biodegradable (plastic packaging) should be left out. The listed wastes are probably not toxic to the biodegradative microflora.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

Table 71: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
See Table 70 above	0.18:1 g O_2/ g CH_2O	~2:1	25 - 80	303	293 - 313	Ambient	0.2 to 10 atm	192 (8 day)	24 – 1152 (1 – 48 days)	Residence time depends on treatment goals (inorganic nutrient recycling has short residence time; organic carbon destruction/CO_2 recovery has longer residence times).
Stoichiometric excess depends on oxygen delivery technology. Oxygen transfer efficiency can be from 10 to 95%, but values in the range of 25 to 50% are most reasonable for modeling at this time.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
Scenario 1: Biodegradable portion of solid waste is approximately 4.371 kg/day. The slurry bioreactor vessel required would be smaller than that for Scenario 3. Operational concerns for microgravity environment would need to be addressed (e.g., supply of oxygen requirement via gravity independent methods such as controlled feed of H_2O_2 based on dissolved oxygen (DO) levels and O_2 consumption rates or use of bubble-less aeration systems).
Scenario 2: Biodegradable portion of solid waste is approximately 4.927 kg/day. The slurry bioreactor vessel required would be smaller than that for Scenario 3. Operational concerns for hypogravity environment would need to be addressed, but are probably not significant.
Scenario 4: Biodegradable portion of solid waste is approximately 10.183 kg/day. CO_2 production, nutrient recovery, and solids reuse are possible. The slurry bioreactor vessel required would be larger than that for Scenario 3. Operational concerns for hypogravity environment would need to be addressed, but are probably not significant.
Scenario 5: Biodegradable portion of solid waste is approximately 16.5 kg/day. CO_2 production, nutrient recovery, and solids reuse are possible. The slurry bioreactor vessel required would be larger than that for Scenarios 3 & 4. Operational concerns for hypogravity environment would need to be addressed but are probably not significant.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

EQUIPMENT/HARDWARE DATA

Table 72: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Slurry bioreactor vessel	TBD	2.0**	0.1**		
2	Air pump, stirring motor	TBD				
3	Solid/liquid separation (filtration)	TBD				
4	Gas/liquid separation (for microgravity)	TBD				

1) Indicate if subassembly would need replacement at some other interval.
2) **This is a maximum value for Scenario 3.

BACKGROUND OR REFERENCE INFORMATION:
Reactor size constraints include:

- Volumetric power input requirements to attain required oxygen transfer rates
- Volumetric power input requirements to maintain completely mixed conditions
- Interaction between 1 and 2 and the effective solids concentration at which the reactor can be operated (solids residence time and ratio of solids residence time to hydraulic residence time directly interact with this as well)

Assuming solids concentration can be run as up to 10% solids reactor size can be as low as 0.1 to 0.2 m^3 for short residence time (nutrient recovery) systems with a reactor size for the nominal case (8 day residence time) calculated as 0.35 m^3.

MAJOR COMPONENT SCALING FACTOR:
None reported.

EQUIPMENT/HARDWARE DATA

Table 73: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Flow meter					
2	Sensors: pH, temperature, dissolved oxygen, off-gas CO_2 analyzer					

1) Indicate if subassembly would need replacement at some other interval.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

BACKGROUND OR REFERENCE INFORMATION:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA THAT IS DIFFERENT FROM SCENARIO 3:
The main difference between scenarios for slurry bioreactors concerns scale. Scale is a direct consequence of biodegradable waste vs. non-biodegradable waste. For the waste types given in the Reference Missions and Waste Model Document, the only ones that change between scenarios are crop residues (increase from 1 $\Rightarrow$ 5) and packaging (decrease from 1 $\Rightarrow$ 5), some of which is biodegradable.

The other major difference in scenarios is associated with the effects of microgravity. An aerobic bioreactor depends upon dissolved oxygen (DO), which is problematic in microgravity due to gas coalescence, etc. A possible solution to this problem is to feed in peroxide, on demand, as DO level falls below some set point. Some aerobic bacteria contain enzymes, catalysis peroxides, which can convert hydrogen peroxide in to O_2 and H_2O. This H_2O_2 -- DO supply concept needs to be tested for potential use in microgravity slurry bioreactors.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

Table 74: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Gravity is needed for gas - liquid exchange (solubilization of oxygen and removal of carbon dioxide). Potential supply of dissolved oxygen by bacterial conversion of H_2O_2 needs to be determined/assessed.
Pretreatment Issues	Research to date has been on dried and milled crop residues. Fresh (undried) and chopped crop residues may be sufficient if not fed in too fast. Human solid wastes should probably be dispersed by blending with water.
Post Treatment Issues	Depends on use of bioreactor effluents. If mineral recycling back to hydroponic crops is desired, then the crop production scientists require that the solution be free of microorganisms - thus solid liquid separation of 0.1 μm diameter particles is needed.
Safety	No issues. Well, maybe survival of human fecal borne pathogens? (This researcher would rather see fecal wastes sterilized immediately after collection. Studies at KSC indicate that feces may not contain enough crop nutrients to be worth bioprocessing for this goal.)
Material	Even though called a slurry bioreactor, hardware surfaces will be colonized by biofilms. Some biofilms are corrosive to the underlying matrix. There are no problems in this area to date, but the maximum time a slurry bioreactor has been run continuously, without draining and cleaning, has been 418 days. Will a longer run show biofilm corrosion problems?
Environmental Issues	See safety. Survival of human fecal pathogens is likely (related study to be addressed at KSC over the next year).
Reliability	Very, if environmental parameters are kept within microbial tolerance range. Temperature less than 45°C, pH between 5 and 8, dissolved oxygen - aeration and stirring systems functional.
Integration: Technology Interactions	Crop/food production, physicochemical combustion technologies, combined solid waste and graywater bioprocessing in the same vessel
Integration: Products of Process and their uses	Well demonstrated at KSC. Crop residues from crop growth chambers to slurry bioreactor. Crop growth chamber condensate water used for water source in slurry bioreactors. Filtered bioreactor effluent recycled back to crop hydroponic production system to replenish crop nutrients. Bioreactor O_2 supplied by plant growth chamber generated O_2. Bioreactor generated CO_2 in the off gas was cycled back to the plant growth chamber. Filter retentate solids have been sent to Ames Research Center and U. of Utah scientists for testing of fluidized bed incinerators and other combustion devices. Bioreactor solids have been tested, on a limited basis, as a solid seed germination support/matrix.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	4 or 5. Preprocessing and post processing components are undesirable. Definite needs for automation (reduce crew interactions) of feeding, harvesting and post processing. One demonstration of near-readiness when crop residues from L/MSLTP phase III were sent to KSC for slurry bioprocessing, with treated effluents sent back to JSC and incorporated into nutrient replenishment for crops being grown in their VPGC.
Estimated Cost of Development to TRL of 5	TBD. Depends on bioprocessing goal and degree of automation desired at higher TRL levels.
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

TECHNOLOGY NAME/TYPE: **Aerobic Completely Mixed (Slurry) Biological Reactor**

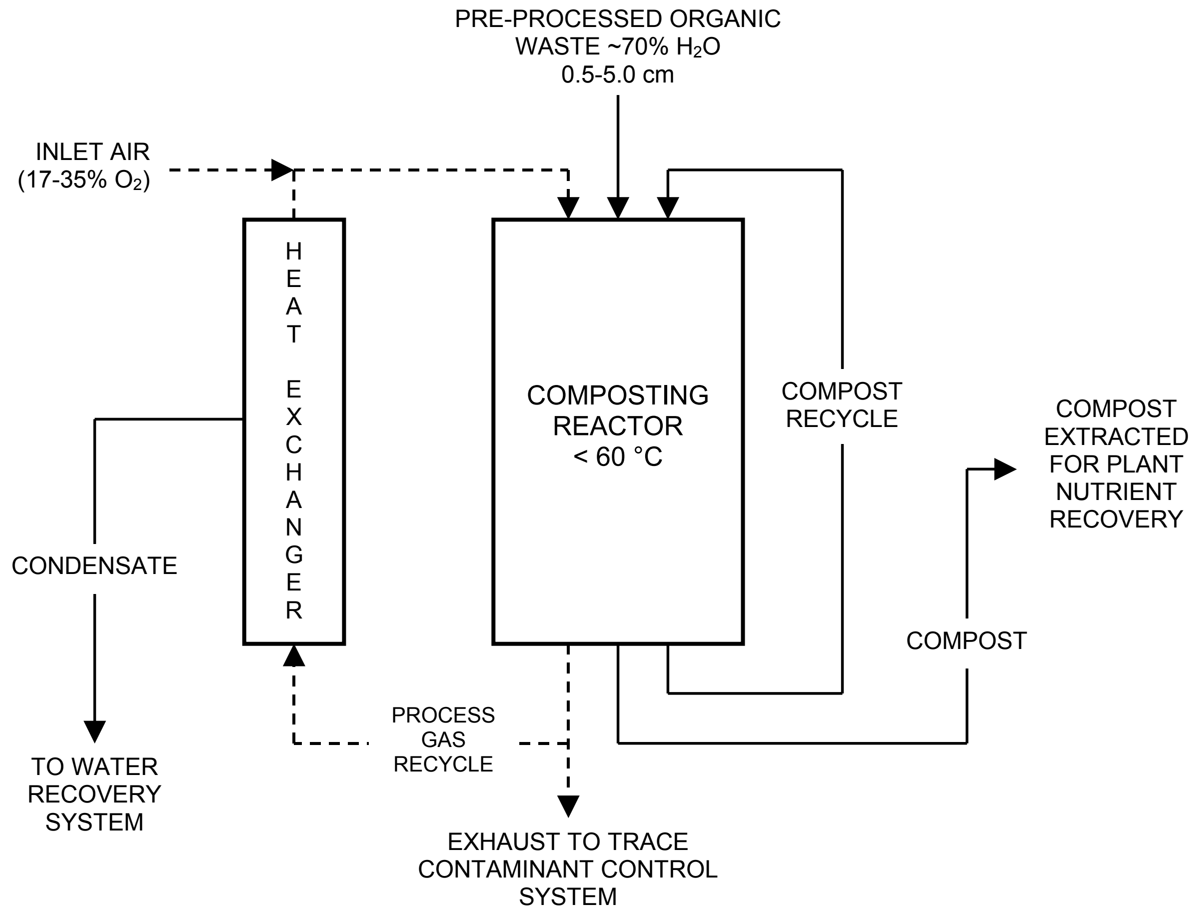
TECHNOLOGY ADVANCES:
1) What other alternate technologies are comparable to this one?
Depends on bioprocessing goals. Faster than composting, slower than fixed-film bioreactor just bioprocessing to recycle nutrients (i.e., NO cellulose or other biopolymer biodegradation).

2) What other type of technologies would help improve this one?
Preprocessing - drying and size reduction.
Post processing - solid liquid separation.
Specifying that ALL packaging, trash, filters, tape, will be biodegradable.

3) What other types of work are currently going on to improve this technology?
Need research on hydrogen peroxide as an alternate source of dissolved oxygen (eliminate microgravity problems of gas-liquid oxygen transfer).
Need a method to remove sodium chloride from urine.
Need a better solid-liquid separation system.
Need bioprocess automation (pretreatment, reactant addition (water, gas, and solids) to bioreactor, bioreactor harvest, and solid-liquid separation.
Need sensors (pH, DO, especially) that don't biofoul.

Composting - Plant Nutrient Extraction Variant 7-Day Residence Time (No curing phase)

Figure 16: Flow Diagram of Plant Nutrient Extraction Technology



TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Processing of inedible plant matter:
$C_4H_5ON + C_6H_{10}O_5 + C_{10}H_{11}O_2 + O_2 \Rightarrow CO_2 + H_2O$ + MICROBIAL BIOMASS + NH_3 + VOCs + COMPOST + HEAT (NOT BALANCED)
Processing of human wastes:
$C_2H_6O_2N_2 + C_{42}H_{69}O_{13}N_5 + C_{13}H_{28}O_{13}N_2 + O_2 \Rightarrow CO_2 + H_2O$ + MICROBIAL BIOMASS + NH_3 + VOCs + COMPOST + HEAT (NOT BALANCED)
The resultant compost will consist mostly of non-degraded recalcitrant molecules such as cellulose, hemicellulose, and lignin as well as water. At a 7-day residence time, only minor humic substance formation will occur. Aside from evaporation driven by heat production and removal, metabolic water production during degradation is approximately 50-65% of the dry organic matter degraded (material dependent).

SIDE REACTIONS:
Anaerobic Conditions:
Various organic wastes + Air (O_2 limiting conditions <3%) $\Rightarrow$ Amides + Organic Acids + Microbial Biomass + Heat

Biological nitrification is mainly carried out by two groups of autotrophic bacteria in a two-stage process at mesophilic temperatures (10-40°C):
(1) $NH_3 + O_2 + 2\ H+ + 2\ e^- \Rightarrow NH_2OH + H_2O \Rightarrow NO_2^- + 5\ H^+ + 4\ e^-$
(2) $NO_2^- + H_2O \Rightarrow NO_3^- + 2\ H^+ + 2\ e^-$
In combination with nitrification, a potential exists for microbial denitrification, which would lead to N_2 production, with possible minor production of NO_x side products. Numerous volatile organic compounds (VOCs) are produced and emitted in the composting exhaust. The identity and quantity of these compounds are dictated by waste composition and O_2 mass transfer characteristics. Various stable macromolecules will be formed in the compost such as humic and fulvic acids. Again, rates are waste specific. Minor amounts of methane production have been observed, even in well-aerated systems.

RATE EXPRESSION (IF POSSIBLE):
$\underline{dm/d\theta \cong k\ (m\text{-}me)}$ where $dm/d\theta$, kg/day
m = compost dry mass, kg
me = equilibrium mass for compost, kg (non-degradable fraction – includes minerals and biologically recalcitrant components such as lignin)
θ = time, day
and k = decomposition rate, 1/day
Although this equation assumes k to be constant, it is not. During the first several days of processing, when easily degradable components are present, k can be quite high. This value will decrease as only more recalcitrant components are left. Experimentation indicated that k averaged 0.18 for the first week of composting of ALS inedible biomass (wheat, soybean, potato and tomato residues). A degradable fraction (*df*) of approximately 50-60% is reasonable.

TYPE OF FEED PREPARATION REQUIRED:
The type of feedstock preparation required prior to composting is waste specific. For inedible biomass, the material must be size reduced. This is preferably done through a shredding type of operation as opposed to a chopping, as shredding can greatly reduce bulk density for certain crops as well as expose internal plant tissue. Size reduction should yield an average particle size of approximately 0.5-5 cm.

A preliminary analysis indicates that combing the various waste fractions will yield a matrix moisture content of ~72%. This value has been demonstrated to be adequate starting moisture content for ALS crop waste composting (no other wastes added). Therefore, it is possible that no moisture conditioning is required for the waste feedstock. It must be noted however, that certain crops such as tomatoes and potatoes have moisture contents that yield free water and drainage when size reduced. If a large harvest of these crops were to be processed without addition of

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

other drier wastes that could absorb this free water, drying would likely be required. It is possible that plants could undergo some deliberate post-harvest drying phase to reduce moisture prior to collection/size reduction.

Regardless of processor type, if large amounts of moist organic material (e.g., inedible biomass) require storage to feed a continuously or semi-continuously fed reactor, provisions must be made to ensure that either the material be prevented from undergoing significant microbial degradation (i.e., drying or freezing) or that the storage vessel simultaneously serves to control the microbial environment in order to prevent undesirable product formation.

With regard to human solid wastes, size reduction is not the issue, but rather proper mixing of feces with other drier and structure-bearing wastes to both reduce moisture and to provide porosity. Dry materials such as paper will require size reduction and mixing with moist fractions to elevate moisture levels.

FEED RATE (kg/hr):

Waste Stream, dry	8.49	kg/day
Waste Stream, wet	38.81	kg/day
Recycled Compost, wet	1.94	kg/day
TOTAL COMPOST MIX	40.75	kg/day

The reactor is not limited to either continuous or batch loading. This system is very flexible with respect to loading. The system can be loaded with as much waste as can be fit into the reactor, or fed in a continuous or semi-continuous manner. For purposes of calculations in this document, it is assumed that the wastes are loaded once a day (8.49 kg dry/day).

TYPE CATALYST/ORGANISMS REQUIRED:
The microbial populations involved in composting are typically indigenous to the waste materials themselves (e.g., plants, feces). Regardless, an initial inoculation (10 grams) would provide higher reliability. Subsequently, the system may be benefited by recycling a minor stream of the process residue (compost) at ~5% v/v with the incoming feedstock. A small supply of lyophilized mixed cultures would insure proper and rapid re-inoculation in response to extreme perturbations.

PROHIBITED WASTES:
Although non-biodegradable wastes that are non-toxic such as plastics (Teflon, PVC) can be included, they will not be degraded and may hinder system efficiency. Microbial toxic compounds such as sterilizing agents are prohibited. Chemically recalcitrant compounds will not necessarily decrease performance, but they will likely undergo little degradation. Caution must be exercised if the compost is to be utilized for other functions such as use in plant growth (i.e., bioaccumulation of metals). Cellulose filters might be acceptable, depending on their actual composition. Tapes would be prohibited. Urine solids could be processed, though the salt contained in them may hinder utilization of the compost for further resource recovery, such as plant nutrient extraction or use as a plant growth medium. For the purposes of this analysis, the following wastes were excluded: Tape, Filters, Miscellaneous (Teflon, Tape, PVC), Plastic Packaging, and Urine Solids.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

Table 75: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
MIXED WASTE(dry) 8.49 kg/day	O_2/DS_{loss} ≈1.37	CO_2/DS_{loss} ≈1.85	35%	323	293-333	101.3	50- 110	7 days, 168 hrs	5-9 days	Air: Waste can be reduced by design of system. Air residence time ~30 sec.
MIXED WASTE(dry) 8.49 kg/day		H_2O/DS_{loss} ≈0.54		323	293-333	101.3	50-110	7 days, 168 hrs	5-9 days	~ half of degraded solids are converted to water.
MIXED WASTE(dry) 8.49 kg/day		Dry Air/DS_{loss} ≈0.46		323	293-333	101.3	50-110	7 days, 168 hrs	5-9 days	
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
No significant changes would be incurred for the process data.
EQUIPMENT/HARDWARE DATA

Table 76: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Composting matrix (wet)	149	0.58	-	N.K.	Compost has 7 day residence time.
2	Filled composting vessel with mechanical turner, motor	194	0.67	N.K.	N.K.	Vessel should last for mission duration.
3	Air Pump, i.e., fan(s)	~ 2	0.002	0.006	N.K.	N.K. (Generally reliable)
4	Heat exchanger (Water Condenser)	N.K.	N.K.	N.K.	N.K.	Should last for mission duration
1) Indicate if subassembly would need replacement at some other interval.						

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

BACKGROUND/REFERENCE INFORMATION:

- Composting/curing vessel is assumed to be 35% of the composting mass.
- Reactor volume is assumed to be 15% greater than that of the organic material.
- Compost bulk density (data from shredded inedible biomass) is assumed be 90 g/L.
- Decay coefficient assumed to be 0.18.
- Average moisture content assumed to be 65%.
- Degradable fraction assumed to be 55%.

EQUIPMENT/HARDWARE DATA

Table 77: MAJOR COMPONENENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1	1	1				Designed to meet the requirements.
2	1	1	1				Designed to meet the requirements.
3	1	1	1				Designed to meet the requirements.
4	1	1	1	Increase w/ rate			Designed to meet the requirements.

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
The components were designed or selected to meet requirements using kinetic theory and experience. The estimates for hardware requirements require further analysis.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

EQUIPMENT/HARDWARE DATA

Table 78: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Flow Meter	0.7	Small	None	None	Suitable for long-term (years) use, though this is dependent on system utilized
2	Temperature Sensor(s)	0.1	Very small	Very small	N.K.	Suitable for long-term (years) use if not abused
3	O_2 Sensor	0.5	Very small	Very small	N.K.	Will likely require replacement annually (biannually?)
4	Valves, tubing, connectors	N.K.	N.K.	N.K.	N.K.	Requires complete design to establish these values
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 79: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1	1	1	None	None	None	Designed to meet the requirements.
2	1	1	1	None	None	None	Designed to meet the requirements.
3	1	1	1	None	None	None	Designed to meet the requirements.
4	1	1	1	None	None	None	Designed to meet the requirements.

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
These components will have the same power, mass and volume requirements regardless of processing rate or reactor size.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:

Scenario 1 – Transit – The wastes amenable to biological processing in Scenario 1 will primarily be waste paper, feces, and any inedible biomass produced. Microgravity would pose design challenges to material translocation into, through, and out of the reactor. To handle the humidified exhaust air, an air/water separator would be required. Composting would serve to sanitize the material and recover water both through evaporation and metabolic water production, but the material would require further processing to recover all physically and chemically bound water. This variant of the composting system (7 days) may require extension of processing duration to fully stabilize waste.

Scenario 2 – Salad Machine – 600 Days – Because the retention time in the composting reactor will likely remain fairly constant, the reactor volume will decrease proportionately with decreased waste loading rates. Certain mass/volume requirements would remain constant such as valves, sensors, etc. regardless of waste input. A salad machine will likely not produce substantial inedible biomass since mostly salad crops will be grown. Therefore, feces and packaging material will remain the primary inputs. If packaging is plastic, it will probably not serve well as a bulking agent for feces, and should not be included. Therefore, the reactor for this scenario would likely require a specialized design that was capable of receiving a high proportion of feces.

Scenarios 4 and 5 – The increased levels of inedible biomass loading would result in nearly proportional increases in reactor volume, mass, and power requirements as compared to Scenario 3.

General Information:

The amount of reactor insulation will affect system temperature and moisture removal. Minimizing conductive/convective heat loss by insulating the reactor shifts heat loss to evaporative cooling, thereby increasing moisture loss. Likewise, insulation will establish increased horizontal temperature uniformity (important for pathogen destruction).

The utilization of air re-circulation in the reactor will allow the aeration and heat removal functions of ventilation to be decoupled. Therefore, fresh air is required only to meet the stoichiometric O_2 requirements, while heat is removed though evaporative cooling. This serves to lower gaseous emission volume and likely the contaminant loading as well.

The current air use design values reflect the use of an “air once through” system (no air re-circulation). It is therefore possible that ventilative air requirements will be up to 5 times less than those presented. Continuous condensation of the process gas (recycling) also promotes the trapping of soluble gases such as NH_3 and VOCs in the condensate, which can then be treated in the water recovery system.

The carbon:nitrogen ratio is an important issue in composting in that it affects rates of decomposition and NH_3 production. The estimated nitrogen and carbon loading of the pertinent wastes indicate that the ratio is low, about 20:1. This supplies an excess of nitrogen, which may increase NH_3 volatilization. Table 80 lists factors affecting the performance of the composting system.

Table 80: Factors affecting performance and operational cost of composting system[1]

Organic Amendment	Ambient Temperature
Bulking Agent	Aeration Schedule
Percent Recycled Compost	Percent Recycled Air
Nutrient Balance, C/N Ratio	Stirring Frequency
Moisture Content	Moisture Control
Particle Size	Retention Time
Porosity	Curing Time
Bulk Density	Pile Shape
pH	Pile Depth
Oxygen Concentration	Pile Volume
Compost Temperature	

[1] Factors presented in boldface are those considered most important in formulation or management of the composting process.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

Of these factors, nutrient balance, moisture content, particle size, porosity and pH are the most important in formulation of the compost mix. Factors such as oxygen concentration, temperature, and water content are the most important during management of the process. A summary of the guidelines for major factors affecting the composting process is presented in Table 81. The reasons behind these guidelines are as follows:

- Microorganisms require an energy source (biodegradable carbon source), nitrogen, and sufficient moisture to thrive during the decomposition process.
- Particle size determines surface area and surface area affects microbial growth. If particles are extremely large, decomposition rates and heat output will be low, increasing composting times and possibly preventing the compost from attaining thermophilic temperatures.
- A predominantly aerobic (in the presence of oxygen) process is preferred over an anaerobic process to minimize odors and provide a high rate of decomposition. Adequate porosity of the compost pile is required to assure an aerobic process. Air containing oxygen must move throughout the matrix (composting pile), whether using forced ventilation or natural convection.
- A near neutral pH is preferred since low pH inhibits growth of the most active microflora and a high pH increases NH_3 loss.

Table 81: Guidelines for major factors affecting composting

Factor	Reasonable Range	Preferred Range
Nutrient balance, C/N	25:1-40:1	30:1 - 40:1
Moisture Content	45-75% w. b.	55-70% w. b.
Particle Size	0.5-5 cm	Depends on Material
Porosity	30-50%	35-45%
Bulk Density	<640 kg/m^3	As high as porosity allows
pH	6.0-9.0	6.5-8.0
Oxygen Concentration	>10%	≥ 15%
Temperature	45-60^{o}C	55-60^{o}C

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

Table 82: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The extent of gravity will affect system characteristics, including matrix density. Air/water separators will be required for exhaust condensation. Design of composting vessel is critical to assure proper movement of material through the system.
Pretreatment Issues	Feedstock required to be ~ 65-75% moisture and size reduced to 0.5-5 cm. Feces will require mixing with a material that will impart porosity such as biomass or paper. Carbon to Nitrogen ratio should be 15-40 (component dependent).
Post Treatment Issues	This system is designed to prepare compost for plant nutrient recovery through aqueous extraction. Little or no post-treatment is required prior to extraction. After aqueous extraction, residue drying or thermal oxidation may be included.
Safety	The reactor system operates at near ambient temperature and pressure. Organic and inorganic components and bioaerosols in the exhaust will require treatment. Compost will be well sanitized, though potential exists for pathogens to remain in extremely small numbers.
Material	Composting reactor material must be constructed of non-corrosive, non-biodegradable, and thermally stable material. Condensers must handle slightly alkaline water (pH = ~8.5-9 due to NH_4^+).
Environmental Issues	Control process temperature above 328 K for 3-4 days at start of the process
Reliability	Composting is a very robust system. Perturbations will likely only result in reduced performance, rather than outright failure. System restart will be rapid. Accidental sterilization will require inoculation with old compost.
Integration: Technology Interactions	Composting reactor can receive “dirty” gases from other waste treatment systems and possibly reduce overall emissions loading. Compost can serve as a plant nutrient source, plant growth medium, and biofilter matrix.
Integration: Products of Process and their uses	CO_2 and H_2O produced. Compost utilization possibilities include aqueous extraction for plant nutrients, use as a plant growth medium, and use as a biofilter matrix for trace chemical contaminant control.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	Current TRL level 4-5. Although much composting research has been conducted, only a small amount has been conducted with respect to ALS environments. Unknown, but small, estimated development costs.
Estimated Cost of Development to TRL of 5	$0.4 million
Estimated Time & Cost to Manufacture a Unit to TRL of 5	2 years
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 7-Day Residence Time**

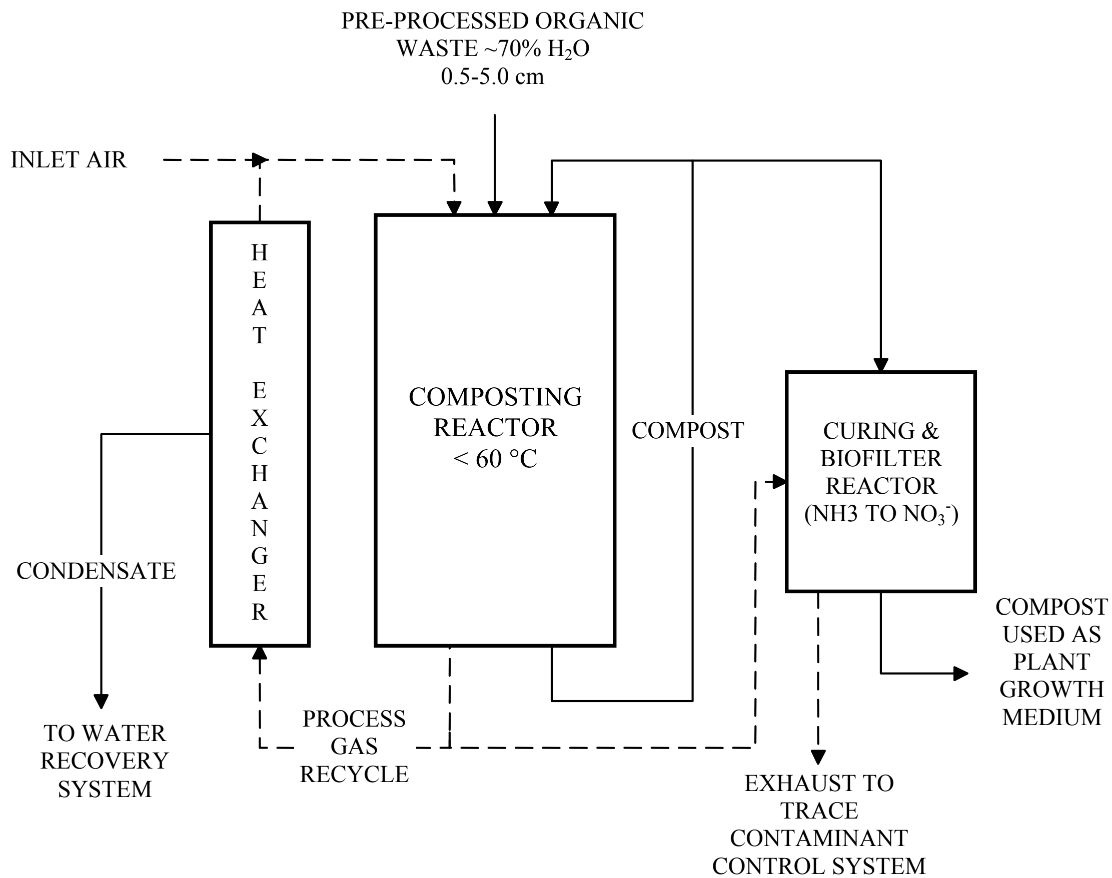
TECHNOLOGY ADVANCES:
1) What other alternate technologies are comparable to this one?
Solid-state fermentation (anaerobic composting) – This involves operating the system in an anaerobic manner, instead of aerobic (composting). This system differs in that it does not operate in a self- heating mode and is typically conducted at higher moisture contents. It requires a separate heat input/stage for temperature control and pathogen destruction. It cannot serve as a biofilter.

2) What other type of technologies would help improve this one?
One of the major hurdles in the design of a continuous composting reactor is automated material translocation. The composting matrix must move uniformly through the reactor and not mix fresh material with older material in order to assure proper sanitation and stabilization of the end product. This indicates the need for a plug-flow system. There are currently no commercial system designs that operate well in this mode, thus requiring this type of technology development. Systems that mix the entire contents of the reactor will need to be run in a batch mode, thereby requiring either significant waste storage or multiple reactors. Also, properly sized feedstock size-reduction systems are required.

3) What other types of work are currently going on to improve this technology?
Research is being conducted at pilot and full scale to determine effects of process air recycling and reversed airflow on process kinetics and odor control of in-vessel (tunnel composting) systems.

Composting - Plant Nutrient Extraction Variant 21 Day Residence Time

Figure 17: Flow Diagram of Plant Nutrient Extraction Variant 21-Day



TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

MAJOR REACTIONS:
Processing of inedible plant matter:
$C_4H_5ON + C_6H_{10}O_5 + C_{10}H_{11}O_2 + O_2 \Rightarrow CO_2 + H_2O$ + MICROBIAL BIOMASS + NH_3 + VOCs + COMPOST + HEAT (NOT BALANCED)
Processing of human wastes:
$C_2H_6O_2N_2 + C_{42}H_{69}O_{13}N_5 + C_{13}H_{28}O_{13}N_2 + O_2 \Rightarrow CO_2 + H_2O$ + MICROBIAL BIOMASS + NH_3 + VOCs + COMPOST + HEAT (NOT BALANCED)

The resultant compost will consist mostly of non-degraded recalcitrant molecules such as cellulose, hemicellulose, and lignin as well as water. At a 21-day residence time, some humic substance formation will occur. Aside from evaporation driven by heat production and removal, metabolic water production during degradation is approximately 50-65% of the dry organic matter degraded (material dependent).

SIDE REACTIONS:
Anaerobic Conditions:
Various organic wastes + Air (O_2 limiting conditions <3%) $\Rightarrow$ Amides + Organic Acids + Microbial Biomass + Heat

Biological nitrification is mainly carried out by two groups of autotrophic bacteria in a two-stage process at mesophilic temperatures (10-40°C):
(1) $NH_3 + O_2 + 2\ H+ + 2\ e^- \Rightarrow NH_2OH + H_2O \Rightarrow NO_2^- + 5\ H^+ + 4\ e^-$
(2) $NO_2^- + H_2O \Rightarrow NO_3^- + 2\ H^+ + 2\ e^-$
In combination with nitrification, a potential exists for microbial denitrification, which would lead to N_2 production, with possible minor production of NO_x side products. Numerous volatile organic compounds (VOCs) are produced and emitted in the composting exhaust. The identity and quantity of these compounds are dictated by waste composition and O_2 mass transfer characteristics. Various stable macromolecules will be formed in the compost, such as humic and fulvic acids. Again, rates are waste specific. Minor amounts of methane production have been observed, even in well-aerated systems.

RATE EXPRESSION (IF POSSIBLE):
$\underline{dm/d\theta \cong k\ (m\text{-}me)}$ where $dm/d\theta$, kg/day
m = compost dry mass, kg
me = equilibrium mass for compost, kg (non-degradable fraction – includes minerals and biologically recalcitrant components such as lignin)
θ = time, day
and k = decomposition rate, 1/day

Although this equation assumes k to be constant, it is not. During the first several days of processing, when easily degradable components are present, k can be quite high. This value will decrease as only more recalcitrant components are left. Experimentation indicated that k averaged 0.18 for the first week of composting of ALS inedible biomass (wheat, soybean, potato and tomato residues). A degradable fraction (*df*) of approximately 50-60% is reasonable.

TYPE OF FEED PREPARATION REQUIRED:
The type of feedstock preparation required prior to composting is waste specific. For inedible biomass, the material must be size reduced. This is preferably done through a shredding type of operation as opposed to a chopping, as shredding can greatly reduce bulk density for certain crops as well as expose internal plant tissue. Size reduction should yield an average particle size of approximately 0.5-5 cm.

A preliminary analysis indicates that combing the various waste fractions will yield a matrix moisture content of ~72%. This value has been demonstrated to be adequate starting moisture content for ALS crop waste composting (no other wastes added). Therefore, it is possible that no moisture conditioning is required for the waste feedstock. It must be noted however, that certain crops such as tomatoes and potatoes have moisture contents that yield free water and drainage when size reduced. If a large harvest of these crops were to be processed without addition of

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

other drier wastes that could absorb this free water, drying would likely be required. It is possible that plants could undergo some deliberate post-harvest drying phase to reduce moisture prior to collection/size reduction.

Regardless of processor type, if large amounts of moist organic material (e.g., inedible biomass) require storage to feed a continuously or semi-continuously fed reactor, provisions must be made to ensure that either significant microbial degradation of the material be prevented (i.e., drying or freezing), or that the storage vessel simultaneously serves to control the microbial environment in order to prevent undesirable product formation.

With regard to human solid wastes, size reduction is not the issue, but rather proper mixing of feces with other drier and structure-bearing wastes to both reduce moisture and to provide porosity. Dry materials such as paper will require size reduction and mixing with moist fractions to elevate moisture levels.

FEED RATE (kg/hr):

Waste Stream, dry	8.49	kg/day
Waste Stream, wet	38.81	kg/day
Recycled Compost, wet	1.94	kg/day
TOTAL COMPOST MIX	40.75	kg/day

The reactor is not limited to either continuous or batch loading. This system is very flexible with respect to loading. The system can be loaded with as much waste as can be fit into the reactor, or fed in a continuous or semi-continuous manner. For purposes of calculations in this document, it is assumed that the wastes are loaded once a day (8.49 kg dry/day).

TYPE CATALYST/ORGANISMS REQUIRED:
The microbial populations involved in composting are typically indigenous to the waste materials themselves (e.g., plants, feces). Regardless, an initial inoculation (10 grams) would provide higher reliability. Subsequently, the system may be benefited by recycling a minor stream of the process residue (compost) at ~5% v/v with the incoming feedstock. A small supply of lyophilized mixed cultures would insure proper and rapid re-inoculation in response to extreme perturbations.

PROHIBITED WASTES:
Although non-biodegradable wastes that are non-toxic such as plastics (Teflon, PVC) can be included, they will not be degraded and may hinder system efficiency. Microbially toxic compounds such as sterilizing agents are prohibited. Chemically recalcitrant compounds will not necessarily decrease performance, but they will likely undergo little degradation. Caution must be exercised if the compost is to be utilized for other functions such as use in plant growth (i.e., bioaccumulation of metals). Cellulose filters might be acceptable, depending on their actual composition. Tapes would be prohibited. Urine solids could be processed, though the salt contained in them may hinder utilization of the compost for further resource recovery, such as plant nutrient extraction or use as a plant growth medium. For the purposes of this analysis, the following wastes were excluded: Tape, Filters, Miscellaneous (Teflon, Tape, PVC), Plastic Packaging, and Urine Solids.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

Table 83: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
MIXED WASTE(dry) 8.49 kg/day	O_2/DS_{loss} ≈1.37	CO_2/DS_{loss} ≈1.85	50-60%	323	293-333	101.3	50- 110	21 days, 504 hrs	19-23 days	Air: Waste can be reduced by design of system. Air residence time ~30 sec.
MIXED WASTE(dry) 8.49 kg/day		H_2O/DS_{loss} ≈0.54		323	293-333	101.3	50-110	21 days, 504 hrs	19-23 days	~ half of degraded solids are converted to water.
MIXED WASTE(dry) 8.49 kg/day		Dry Air/DS_{loss} ≈0.46		323	293-333	101.3	50-110	21 days, 504 hrs	19-23 days	
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
No significant changes would be incurred for the process data.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

EQUIPMENT/HARDWARE DATA

Table 84: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Composting matrix (wet)	365	1.42	-	N.K.	Compost has 21-day residence time.
2	Composting vessel with compost, mechanical turner, motor	559	0.67	N.K.	N.K.	Vessel should last for mission duration.
3	Air Pump, i.e., fan(s)	~ 4	0.004	0.012	N.K.	N.K. (Generally reliable)
4	Heat exchanger (Water Condenser)	N.K.	N.K.	N.K.	N.K.	Should last for mission duration
5	Curing stage matrix (wet)	186	0.64	-	N.K	Compost has 21-day residence time. *
6	Curing stage reactor with compost, unloader	251	0.73	N.K	N.K	Vessel should last for mission duration.

1) Indicate if subassembly would need replacement at some other interval.

*Curing reactor residence time is not yet known for certain. 21 days was chosen as a plausible estimate. It is possible that this value could be reduced significantly (e.g., 14 days), with concomitant savings in hardware and power.

BACKGROUND/REFERENCE INFORMATION:
- Composting/curing vessel is assumed to be 35% of the composting mass.
- Reactor volume is assumed to be 15% greater than that of the organic material.
- Compost bulk density (data from shredded inedible biomass) is assumed be 90 g/L for composting, 130 g/L for curing.
- Decay coefficient assumed to be 0.18 for composting, 0.01 for curing.
- Average moisture content assumed to be 65% for composting, 55% for curing.
- Degradable fraction assumed to be 55% for composting, 10% for curing.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

Table 85: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1	1	1				Designed to meet the requirements.
2	1	1	1				Designed to meet the requirements.
3	1	1	1				Designed to meet the requirements.
4	1	1	1	Increase w/rate			Designed to meet the requirements.
5	1	1	1				Designed to meet the requirements.
6	1	1	1				Designed to meet the requirements.

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
The components were designed or selected to meet requirements using kinetic theory and experience. The estimates for hardware requirements require further analysis.

Table 86: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Flow Meter	0.7	Small	None	None	Suitable for long term (years) use, though this is dependent on system utilized.
2	Temperature Sensor(s)	0.1	Very small	Very small	N.K.	Suitable for long term (years) use if not abused.
3	O_2 Sensor	0.5	Very small	Very small	N.K.	Will likely require replacement annually (biannually?)
4	Valves, tubing, connectors	N.K.	N.K.	N.K.	N.K.	Requires complete design to establish these values.

1) Indicate if subassembly would need replacement at some other interval.

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

Table 87: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1	1	1	None	None	None	Designed to meet the requirements.
2	1	1	1	None	None	None	Designed to meet the requirements.
3	1	1	1	None	None	None	Designed to meet the requirements.
4	1	1	1	None	None	None	Designed to meet the requirements.

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.
Note: These components will have the same power, mass and volume requirements regardless of processing rate or reactor size.

TECHNOLOGY NAME/TYPE: **Pneumatic Transport – Dry Material**

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Scenario 1 – Transit – The wastes amenable to biological processing in Scenario 1 will primarily be waste paper, feces, and any inedible biomass produced. Microgravity would pose design challenges to material translocation into, through and out of the reactor. To handle the humidified exhaust air, an air/water separator would be required. Composting would serve to sanitize the material and recover water both through evaporation and metabolic water production, but the material would require further processing to recover all physically and chemically bound water. Unless primarily used for biofiltration purposes, the curing stage would likely be unnecessary in that it is improbable that compost would be used for plant growth.

Scenario 2 – Salad Machine – 600 Days – Because the retention time in the composting reactor will likely remain fairly constant, the reactor volume will decrease proportionately with decreased waste loading rates. Certain mass/volume requirements would remain constant such as valves, sensors, etc., regardless of waste input. A salad machine will likely not produce substantial inedible biomass since mostly salad crops will be grown. Therefore, feces and packaging material will remain the primary inputs. If packaging is plastic, it will probably not serve well as a bulking agent for feces, and should not be included. Therefore, the reactor for this scenario would likely require a specialized design that was capable of receiving a high proportion of feces. As with Scenario 1, the curing stage would most likely serve only as a biofilter, rather than a means of preparing compost for use as a plant growth medium.

Scenarios 4 and 5 – The increased levels of inedible biomass loading would result in nearly proportional increases in reactor volume, mass, and power requirements as compared to Scenario 3.

General Information:
The amount of reactor insulation will affect system temperature and moisture removal. Minimizing conductive/convective heat loss by insulating the reactor shifts heat loss to evaporative cooling, thereby increasing moisture loss. Likewise, insulation will establish increased horizontal temperature uniformity (important for pathogen destruction).

The utilization of air recirculation in the reactor will allow the aeration and heat removal functions of ventilation to be de-coupled. Therefore, fresh air is required only to meet the stoichiometric O_2 requirements, while heat is removed though evaporative cooling. This serves to lower gaseous emission volume and likely the contaminant loading as well.

The current air use design values reflect the use of an “air once through” system (no air recirculation). It is therefore possible that ventilative air requirements will be up to 5 times less than those presented. Continuous condensation of the process gas (recycling) also promotes the trapping of soluble gases such as NH_3 and VOCs in the condensate, which can then be treated in the water recovery system.

The carbon:nitrogen ratio is an important issue in composting in that it affects rates of decomposition and NH_3 production. The estimated nitrogen and carbon loading of the pertinent wastes indicate that the ratio is low ~20:1. This supplies an excess of nitrogen, which may increase NH_3 volatilization.

Table 88 lists factors affecting the performance of the composting system. Of these factors, nutrient balance, moisture content, particle size, porosity, and pH are the most important in formulation of the compost mix. Factors such as oxygen concentration, temperature, and water content are the most important during management of the process. A summary of the guidelines for major factors affecting the composting process are presented on the next page in Table 89. The reasons behind these guidelines are as follows:

- Microorganisms require an energy source (biodegradable carbon source), nitrogen and sufficient moisture to thrive during the decomposition process.
- Particle size determines surface area and surface area affects microbial growth. If particles are extremely large, decomposition rates and heat output will be low, increasing composting times and possibly preventing the compost from attaining thermophilic temperatures.
- A predominantly aerobic (in the presence of oxygen) process is preferred over an anaerobic process to minimize odors and provide a high rate of decomposition. Adequate porosity of the compost pile is

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

required to assure an aerobic process. Air containing oxygen must move throughout the matrix (composting pile), whether using forced ventilation or natural convection.

- A near neutral pH is preferred since low pH inhibits growth of the most active microflora and a high pH increases NH_3 loss.

Table 88: Factors affecting performance and operational cost of composting system[1]

Organic Amendment	Ambient Temperature
Bulking Agent	Aeration Schedule
Percent Recycled Compost	Percent Recycled Air
Nutrient Balance, C/N Ratio	Stirring Frequency
Moisture Content	Moisture Control
Particle Size	Retention Time
Porosity	Curing Time
Bulk Density	Pile Shape
PH	Pile Depth
Oxygen Concentration	Pile Volume
Compost Temperature	

[1] Factors presented in boldface are those considered most important in formulation or management of the composting process.

Table 89: Guidelines for major factors affecting composting

Factor	Reasonable Range	Preferred Range
Nutrient balance, C/N	25:1-40:1	30:1 - 40:1
Moisture Content	45-75% w. b.	55-70% w. b.
Particle Size	0.5-5 cm	Depends on Material
Porosity	30-50%	35-45%
Bulk Density	<640 kg/m^3	As high as porosity allows
PH	6.0-9.0	6.5-8.0
Oxygen Concentration	>10%	≥ 15%
Temperature	45-60^{o}C	55-60^{o}C

TECHNOLOGY NAME/TYPE: **Pneumatic Transport – Dry Material**

Table 90: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The extent of gravity will affect system characteristics, including matrix density. Air/water separators will be required for exhaust condensation. Design of composting vessel is critical to assure proper movement of material through the system.
Pretreatment Issues	Feedstock required to be ~ 65-75% moisture and size reduced to 0.5-5 cm. Feces will require mixing with a material that will impart porosity such as biomass or paper. Carbon to Nitrogen ratio should be 15-40 (component dependent).
Post Treatment Issues	This system is designed to prepare compost for use as a plant growth medium. It may require an initial rinse (possibly "in place" in the growth chamber) prior to use to remove sodium.
Safety	The reactor system operates at near ambient temperature and pressure. Organic and inorganic components and bioaerosols in the exhaust will require treatment. Compost will be well sanitized, though potential exists for pathogens to remain in extremely small numbers.
Material	Composting reactor material must be constructed of non-corrosive, non-biodegradable, and thermally stable material. Condensers must handle slightly alkaline water (pH = ~8.5-9 due to NH_4^+).
Environmental Issues	Control process temperature above 328 K for 3-4 days at start of the process
Reliability	Composting is a very robust system. Perturbations will likely only result in reduced performance, rather than outright failure. System restart will be rapid. Accidental sterilization will require inoculation with old compost.
Integration: Technology Interactions	Composting reactor can receive "dirty" gases from other waste treatment systems, and possibly reduce overall emissions loading. Compost can serve as plant nutrient source, plant growth medium, and biofilter matrix.
Integration: Products of Process and their uses	CO_2 and H_2O produced. Compost utilization possibilities include aqueous extraction for plant nutrients, use as a plant growth medium, use as a biofilter matrix for trace chemical contaminant control.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	Current TRL level 4-5. Although much composting research has been conducted, only a small amount has been conducted with respect to ALS environments. Biofiltration research required. Unknown, but small, estimated development costs.
Estimated Cost of Development to TRL of 5	$0.5 million
Estimated Time & Cost to Manufacture a Unit to TRL of 5	2-3 years
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

TECHNOLOGY NAME/TYPE: **Composting - Plant Nutrient Extraction Variant 21-Day Residence Time**

TECHNOLOGY ADVANCES:

1) What other alternate technologies are comparable to this one?

Solid-state fermentation (anaerobic composting) – This involves operating the system in an anaerobic manner, instead of aerobic (composting). This system differs in that it does not operate in a self-heating mode and is typically conducted at higher moisture contents. It requires a separate heat input/stage for temperature control and pathogen destruction. It cannot serve as a biofilter.

2) What other type of technologies would help improve this one?

One of the major hurdles in the design of a continuous composting reactor is automated material translocation. The composting matrix must move uniformly through the reactor, and not mix fresh material with older material in order to assure proper sanitation and stabilization of the end product. This indicates the need for a plug-flow system. There are currently no commercial system designs that operate well in this mode, thus requiring this type of technology development. Systems that mix the entire contents of the reactor will need to be run in a batch mode, thereby requiring either significant waste storage or multiple reactors.

Properly sized feedstock size-reduction systems are required.

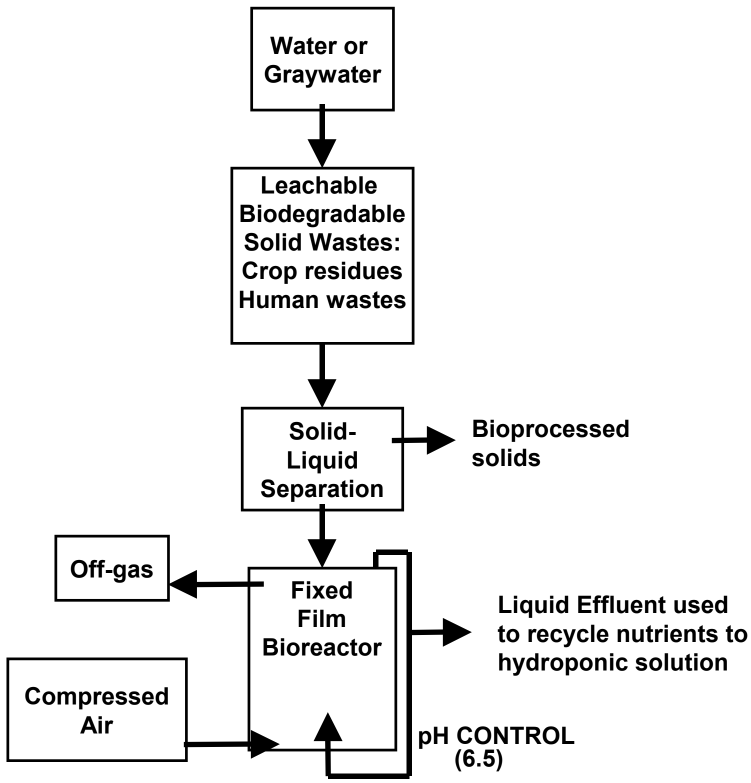
Biofilter development using composts would help.

3) What other types of work are currently going on to improve this technology?

Research is being conducted at pilot and full scale to determine effects of process air recycling and reversed airflow on process kinetics and odor control of in-vessel (tunnel composting) systems. Work is being performed on identification and biofiltration of composting off-gases.

Fixed-Film Bioreactor

Figure 18: Flow Diagram of Fixed-Film Bioreactor Technology



TECHNOLOGY NAME/TYPE: **Fixed-Film Bioreactor**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Soluble biodegradable compounds from aqueous extraction (i.e., leached) crop residues and human solid wastes (generally, carbohydrates -- soluble monosaccharides and polysaccharides/hemicelluloses)
$CH_2O + O_2 \leftrightarrow CO_2 + H_2$
Generalized carbohydrate

SIDE REACTIONS:
Denitrification, if low oxygen conditions are allowed.
$NO_3 + CH_2O \leftrightarrow N_2 + H_2O + CO_2$ (equation NOT balanced)
$NO_3 + CH_2O \leftrightarrow NH3 + H_2O + CO_2$ is also possible. (again, equation NOT balanced)

RATE EXPRESSION (IF POSSIBLE):
Soluble organic compounds/monosaccharides and some oligo- and polysaccharides, can be completely biodegraded. Hydraulic retention time - to be determined/unknown. Probably on the order of 1 to 3 hours.

TYPE OF FEED PREPARATION REQUIRED:
Drying of crop residues: oven -dry at 70^oC to constant weight OR freeze dry (usually 2 weeks). FRESH chopped crop residues - soluble biodegradable organic compounds are minimal.

Milling of crop residues: to 2 mm diameter. Probably will be able to take CHOPPED (2 cm length) crop residues in leaching component.

Leaching/aqueous extraction of biodegradable ALS solid wastes by water or graywater for ca. 2 hours. Automated leaching needs to be developed.

FEED RATE (kg/hr):
6.27 kg/day (calculated from daily crop residue, human solid wastes, and food processing wastes for Scenario #3). Of this, ca. 17% (or 1.07 kg/day) will be soluble organic compounds, of which 80% (or 0.86 kg/day) will probably be biodegraded in a fixed-film bioreactor (estimates from slurry bioreactor biodegradation of soluble TOC = 80%).

TYPE CATALYST/ORGANISMS REQUIRED:
No catalyst required. Inoculum for a mixed microbial biofilm community that can biodegrade soluble organic compounds from crop residues and human solid wastes will need to be developed.

PROHIBITED WASTES:
Anything not biodegradable (e.g., plastic packaging) should be left out. None of the listed wastes are probably toxic to the biodegrading microflora.

TECHNOLOGY NAME/TYPE: **Fixed-Film Bioreactor**

Table 91: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Aqueous extractable/soluble organics from crop residues and human solid wastes	0.18:1[#]		75% of ca. 20%	308	298 - 318	Ambient	Ambient	3	1 - 6	Hydraulic residence time estimated. TBD/Unknown
*Added reactant would be any consumable (O_2, Air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess. [#] Calculated as grams O_2 consumed: grams generic carbohydrate degraded										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None recorded.

Scenario 1: Biodegradable portion of solid waste is approximately 2.51 kg/day, of which 0.43 kg/day is probably soluble organic compounds and 0.34 kg/day can probably be biodegraded in a fixed-film bioreactor. The fixed-film bioreactor vessel required would be smaller than that for Scenario 3. Operational concerns for microgravity environment would need to be addressed (e.g., supply oxygen requirement via controlled feed of H_2O_2 based on DO levels and O_2 consumption rates).

Scenario 2: Biodegradable portion of solid waste is approximately 3.07 kg, of which 0.53 kg/day is probably soluble organic compounds and 0.42 kg/day can probably be biodegraded in a fixed-film bioreactor. The fixed-film bioreactor vessel required would be smaller than that for Scenarios 1 & 3. Operational concerns for microgravity environment would need to be addressed (e.g., supply oxygen requirement via controlled feed of H_2O_2 based on DO levels and O_2 consumption rates).

Scenario 4: Biodegradable portion of solid waste is approximately 8.32 kg, of which 1.43 kg/day is probably soluble organic compounds and 1.14 kg/day can probably be biodegraded in a fixed-film bioreactor. CO_2 production, nutrient recovery, and solids reuse are possible. The fixed-film bioreactor vessel required would be larger than that for Scenario 3. Operational concerns for hypogravity environment would need to be addressed, but are probably not significant.

Scenario 5: Biodegradable portion of solid waste is approximately 14.64 kg, of which 2.51 kg/day is probably soluble organic compounds and 2.01 kg/day can probably be biodegraded in a fixed-film bioreactor. CO_2 production, nutrient recovery, and solids reuse are possible. The fixed-film bioreactor vessel required would be larger than that for Scenarios 3 & 4. Operational concerns for hypogravity environment would need to be addressed, but are probably not significant.

TECHNOLOGY NAME/TYPE: **Fixed-Film Bioreactor**

EQUIPMENT/HARDWARE DATA

Table 92: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Drying oven, freeze dryer (or none,if fresh)- pretreatment component	TBD				
2	Chopper or mill - pretreament component for size reduction	TBD				
3	Solid/liquid separation (filtration)	TBD				
4	Fixed-film bioreactor vessel	TBD				
5	Air pump, stirring motor	TBD				
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors. **Note:** These components will have the same power, mass and volume requirements regardless of processing rate or reactor size.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR:
None reported.

Table 93: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Flow Meter					
2	Sensor(s): pH, temperature, DO, offgas, CO_2 analyzer					
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Fixed-Film Bioreactor**

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
The main differences between scenarios for fixed-film bioreactors concern scale. Scale is a direct consequence of biodegradable waste vs. nonbiodegradable waste. For the waste types given in the Reference Missions and Waste Model Document, the only relevant type for a fixed-film bioreactor that changes between scenarios is crop residue (increase from 1 → 5).

The other major difference in scenarios is the effects of microgravity. An aerobic fixed-film bioreactor depends upon dissolved oxygen, which is problematic in microgravity due to gas coalescence, etc. A possible solution to this problem is to feed in peroxide, on demand, as DO level falls below some set point. Some aerobic bacteria contain enzymes, catalases peroxidases, that can convert hydrogen peroxide in to O_2 and H_2O. This H_2O_2 -- DO supply concept needs to be tested for potential use in microgravity slurry bioreactors.

TECHNOLOGY NAME/TYPE: **Fixed-Film Bioreactor**

Table 94: PERTINENT CRITERIA/ISSUES

Criteria/Issue*	Remarks/Comments
Gravity Dependence	Gravity needed for gas - liquid exchange (solublization of oxygen and removal of carbon dioxide). Potential supply of dissolved oxygen by bacterial conversion of H_2O_2 needs to be determined/assessed.
Pretreatment Issues	Research at KSC has shown that significant amounts of either recyclable minerals OR soluble organic compounds can be leached from fresh crop residues. Thus, crop residues should be dried (oven or freeze drying) prior to leaching. Size reduction: milling to 2 mm or chopping to 2-cm length prior to leaching.
Post Treatment Issues	Removal of sloughed biofilm material from a mature fixed-film bioreactor may be significant. Probably need to remove biofilm-derived particulates by coarse filtration or settling chamber.
Safety	No issues? Well, maybe survival of human fecal borne pathogens, but those that are bacterial size or greater will be retained in the solids fraction after the leaching step. (I'd rather see fecal wastes sterilized immediately after collection. Studies at KSC indicate that feces may not contain enough crop nutrients to be worth bioprocessing for this goal.) Operational parameters - temperature and pressure are ambient or just slightly elevated (35^oC - 308^oK).
Material	No issues?
Environmental Issues	See safety. Survival of human fecal pathogens is likely (related study to be addressed at KSC over the next year).
Reliability	Unknown, but fixed-film bioreactors are commonly used in ground-based applications (sewage treatment - trickling filters, commercial production of specialty chemicals, etc.).
Integration: Technology Interactions	Crop/food production, PC combustion technologies, combined solid waste leachate and graywater bioprocessing in the same vessel, fate of leached solids -- composting, combustion, storage (stable?)
Integration: Products of Process and their uses	Crop residues from crop growth chambers to leachate pretreatment step of fixed-film bioreactor. Crop growth chamber condensate water can be used for water source in fixed-film bioreactors. Filtered (to remove biofilm sloughed material) bioreactor effluent recycled back to crop hydroponic production system to replenish crop nutrients. Bioreactor oxygen supplied by plant growth chamber generated O_2. Bioreactor-generated CO_2 in the offgas can be cycled back to the plant growth chamber. Filter retentate solids can be feed material for composters, fluidized bed incinerators and other combustion devices. Filtration solids may be useful as a solid seed germination support/matrix.
Current Technology Readiness Level (TRL)** + Development Cost To Current TRL	TRL 2. Cost TBD.
Estimated Cost of Development to TRL of 5	DON'T KNOW. Depends on bioprocessing goal and degree of automation desired at higher TRL levels.
Estimated Time & Cost to Manufacture a Unit to TRL of 5	3 - 5 years? ~ \$150,000 $year^{-1}$?

TECHNOLOGY NAME/TYPE: **Fixed-Film Bioreactor**

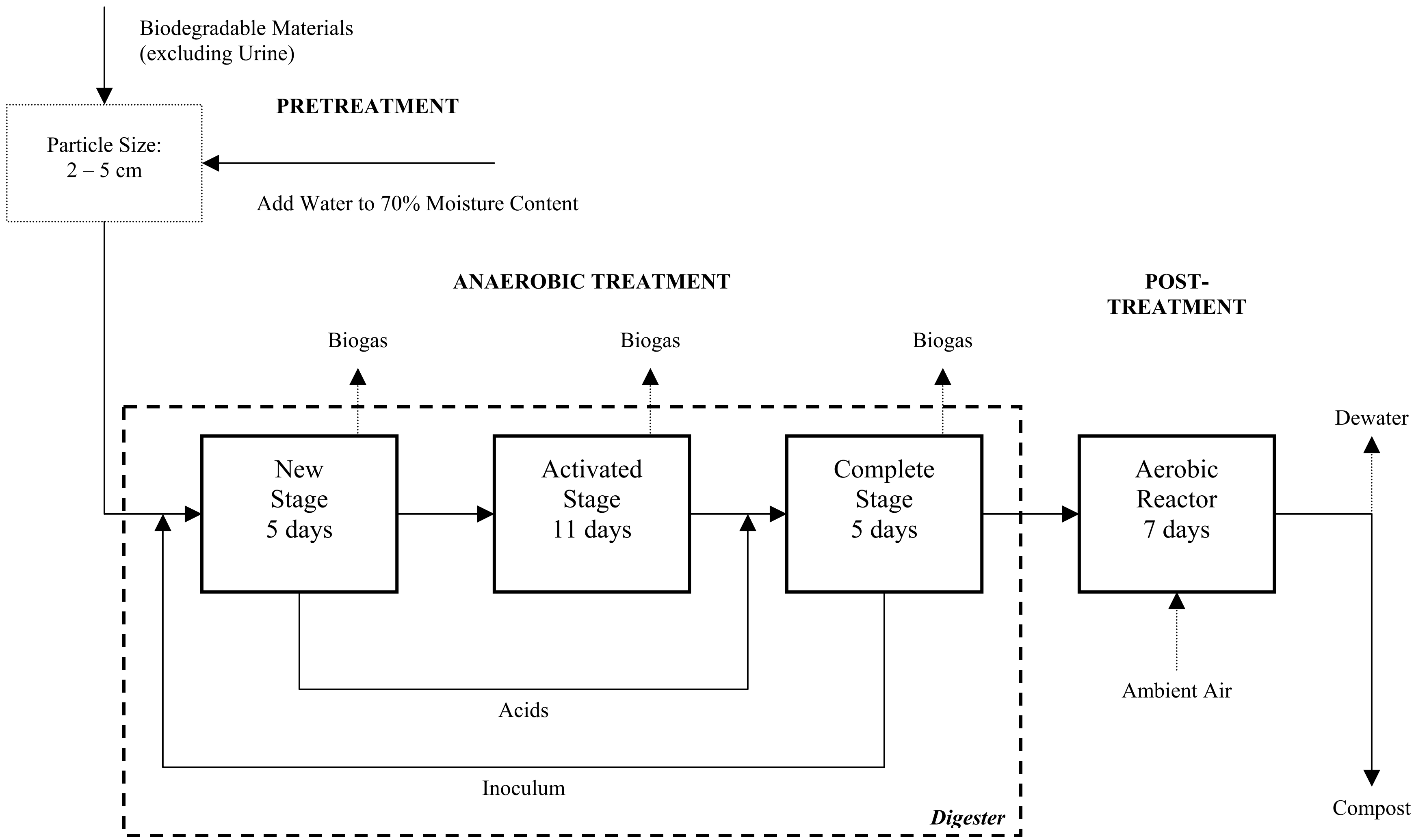
TECHNOLOGY ADVANCES:
1) What other alternate technologies are comparable to this one?
Slurry bioreactor operated at rapid hydraulic retention time on either leached ALS solid wastes or including solids (i.e., no leaching step). Depends on bioprocessing goals -- which would be rapid recovery of minerals with biodegradation/stabilization of soluble organic compounds so bioreactor effluents can be used for replenishment of crop hydroponic solutions. Fixed-film bioreactors should be faster/smaller than slurry bioreactors due to retention of "catalyst" (actively metabolized microbial biofilm attached to surfaces vs. washed out in slurry bioreactor -- although these can be recycled).

2) What other type of technologies would help improve this one?
Preprocessing - drying and size reduction., solid-liquid separation
Postprocessing - coarse filtration or settling to remove sloughed biofilm

3) What other types of work are currently going on to improve this technology?
Need research on hydrogen peroxide as an alternate source of dissolved oxygen (eliminate microgravity problems of gas-liquid oxygen transfer).
Need a method to remove sodium chloride from urine.
Need better solid-liquid separation systems.
Need bioprocess automation (pretreatment, reactant addition (water, gas, solids) to bioreactor, bioreactor harvest, solid-liquid separation).
Need sensors (pH, DO, especially) that don't biofoul.

High-Solids Leach Bed Anaerobic Digestion using SEBAC™ Process

Figure 19: Diagram of High-Solids Leach Bed Anaerobic Digestion Technology



TECHNOLOGY NAME/TYPE: High-Solids Leach Bed Anaerobic Digestion using SEBAC™ Process

PROCESS DATA (NOMINAL & RANGES) – See Figure 19

Digester Operating Conditions:
Temperature: 55°C
Reactor Volume: 0.79 m^3 per reactor, including 25% space for leachate collection and headspace. Physically, there are four such reactor vessels.

Biomass is held within porous baskets.

Feed Bulk Density:
90 $kg_{dry\ weight}/m^3$

Leachate is recycled between the Complete and New Stages for 5 days. This process wets the biomass, adds nutrients and inoculum, and removes volatile acids to prevent inhibition during start-up.
Leachate is recycled within the Activated Stage.
Stages occur sequentially in the same reactor and biomass is not moved.

Post-Treatment:
Digester effluent is aerobically treated for 7 days using room air to further stabilize compost.
The compost may serve as a biofilter to partially clean ambient air.

Solid Mass Balance (Basis: Six People):
8.1 kg/d Biodegradable Solid Material ➔ 1.1 kg/d CH_4 (1.5 m^3) + 3.0 kg/d CO_2 (1.5 m^3) + 4.0 kg/d Compost (or 2.9 kg/d following the Aerobic Step)

I. Collection of Wastes

A. Feces and toilet paper would be collected into biodegradable paper containers.
B. Urine would be collected and treated separately.
C. Other minor human secretions reside in the wash water or are associated with wipes.
D. All paper used for wipes, plates, etc., will be composed of biodegradable materials. These will be collected in dry waste gas-tight containers and kept separate from plastic and other non-biodegradable wastes. These will be emptied into a centralized dry-waste container.
E. All wash waters will be collected and stored into a single gray-water reservoir.

II. Quantities of Wastes by Category (kg/day for a Crew of 6)

Category	Total Solids	Ash	Water	Treatment Method
Biodegradable Wastes	8.1	1.2	18	High-Solids Anaerobic Digestion
Liquid Wastes	TBD	TBD	TBD	Biological Filter (possibly anaerobic) followed by UV, ozone, RO
Non-Biodegradable Dry Wastes	10.6	TBD	0	Incineration or Pyrolysis
Gases				Biological Filter, Other Filters

TECHNOLOGY NAME/TYPE: High-Solids Leach Bed Anaerobic Digestion using SEBAC^{TM} Process

PROCESS DATA (NOMINAL & RANGES) – See Figure 19

III. Treatment of Biodegradable Wastes by Anaerobic Digestion

A. Pretreatment - Wastes are macerated by adding enough liquid waste and/or recycled AD water to make the water content 65% and passing it through a high-solids macerator pump.

B. Anaerobic Digestion - The high-solids sequential batch anaerobic composting process (SEBACTM) is suggested for conversion of wastes into methane, carbon dioxide, and compost. The process involves three stages of digestion that occur sequentially as conversion proceeds. Once within the digester, the waste does not move but passes through the various stages of treatment in place. That is, there are four 0.8 m3 reactors and different stages of treatment at all times. The shredded waste (7-day inventory) is placed into the new reactor. Recirculation of leachate between reactors at the new and final stages inoculates and adds inorganic matter needed for startup. Volatile acids formed during startup are conveyed from the new to the final reactor for conversion. After startup (7 days), the reactor is mature and leachate is recycled upon itself to keep the system moist. For the third stage, the final stage is recycled with a new stage for startup. If well insulated, this three-reactor system will operate at 50ºC and affect 60 to 90% (depends on quality of paper used) conversion of the volatile solids. Note that this system is on a seven-day cycle; i.e., it is fed every 7 days. The waste is collected for 7 days, the digester residence time is 21 days, and the post-treatment residence time is 7 days.

C. Post-Treatment - After anaerobic digestion is complete (21 days), the remaining solids are aerated for 1 to 7 days to remove lingering reduced compounds and dewater to 50%. The solids will be used for compost and wastewater for required process recycle and plant growth. This process step may be used as a biofilter to clean the ambient air.

D. Methane - The biogas is collected and stored under pressure. It can be used directly as an energy source; some cleanup may be necessary to remove hydrogen sulfide.

E. State of Development - The anaerobic digestion technology has been developed to the pilot scale for use on land and can be easily modified for the gravity-free environment in space. Use of the compost to treat wastewater through biofiltration has not been evaluated.

MAJOR REACTIONS:
The waste is primarily paper. Where possible, use wipes, disposable containers, etc., composed of highly biodegradable disposable paper.
Equation: $C_6H_{12}O_6 \rightarrow 3\ CH_4 + 3\ CO_2$

SIDE REACTIONS:
Proteins $\rightarrow$ $CH_4 + CO_2 + H_2S + NH_3$
Fats $\rightarrow$ $CH_4 + CO_2$
These reactions are minor relative to the primary reaction for carbohydrates.

TECHNOLOGY NAME/TYPE: High-Solids Leach Bed Anaerobic Digestion using SEBAC^{TM} Process

PROCESS DATA (NOMINAL & RANGES) – See Figure 19

RATE EXPRESSION (IF POSSIBLE):
Retention Time = 21 d (excluding post-treatment)
Loading Rate = 4.3 kg Total Solids/m^3/d
Methane Yield = 0.21 m^3/kg added
Methane Production Rate = 0.9 m^3/m^3 digester
volume/d

TYPE OF FEED PREPARATION REQUIRED:
Shred to approximately 2.5 cm.
Add water to total solid content of 30%.

FEED RATE (kg/hr):
Feed Rate = 8.1 kg Total Solids/d = 0.34 kg/h
Feed in batch once per seven days = 56.7 kg/7 d

TYPE CATALYST/ORGANISMS REQUIRED:
Digester effluent starter culture is needed once for initial startup. This process requires about 0.1 m^3.

PROHIBITED WASTES:
Prohibited wastes include toxic metals, organic compounds, plastics, glass, and refractory materials.

TECHNOLOGY NAME/TYPE: High-Solids Leach Bed Anaerobic Digestion using SEBAC™ Process

Table 95: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
feces, food, and paper	0	0, if compost is a desirable product	60 - 90	323	10%	13.8	10%	672	10%	
*Added reactant would be any consumable (O_2, Air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
It may be possible to use the compost to treat the gray (wash) water and gases, but this has not been attempted. An attach-film anaerobic digester may be suitable for treatment of gray water, but this has not been addressed yet.

EQUIPMENT/HARDWARE DATA

Table 96: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	2 feed storage vessels	TBD	0.5	0	0	
2	1 macerator pump	TBD	TBD	TBD	TBD	
3	4 digester vessels	TBD	0.8 each	TBD	TBD	The volume may be reduced to 0.4 m^3 each by compacting the feed to 200 $kg_{dry\ weight}/m^3$ and reducing the retention time (based on the biodegradation rate of the feed).
4	1 gas collection vessel	TBD	0.5			
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR & MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3: This system would be suitable for Scenarios 2, 3, 4, and 5, but not for Scenario 1.

TECHNOLOGY NAME/TYPE: High-Solids Leach Bed Anaerobic Digestion using SEBAC™ Process

Table 97: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Some design and operation modification for handling of liquids and gases
Pretreatment Issues	Maceration to 2.5 cm particle size
Post Treatment Issues	Use compost and liquid to grow plants or as a biofilter.
Safety	Methane is explosive.
Material	Emphasis should be placed on producing biodegradable wastes.
Environmental Issues	Removal of hydrogen sulfide from biogas
Reliability	Very reliable compared to other anaerobic digestion designs
Integration: Technology Interactions	Residues may be post-treated and recycled into fuel cells, or they can be used to reform CO, or as part of a methanization digester, or as part of a thermal conversion unit.
Integration:Products of process and their uses	How to use methane and compost
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	Level 4
Estimated Cost of Development to TRL of 5	$500K
Estimated Time & Cost to Manufacture a Unit to TRL of 5	6 - 12 months
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

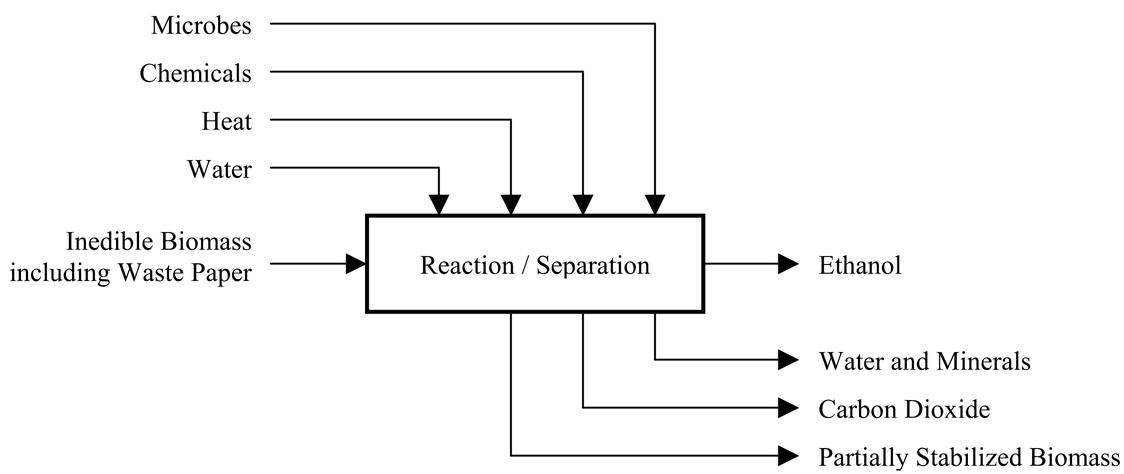
1) What other alternate technologies are comparable to this one?
Aerobic composting: Requires energy and aeration, but it does not produce methane.

2) What other type of technologies would help improve this one?
Methane separation from biogas and production of hydrogen instead of methane

3) What other types of work are currently going on to improve this technology?
Commercialization of larger scale units with capacities of tens to thousands of tons per day
Testing of various feed stocks
Methane enrichment during anaerobic digestion

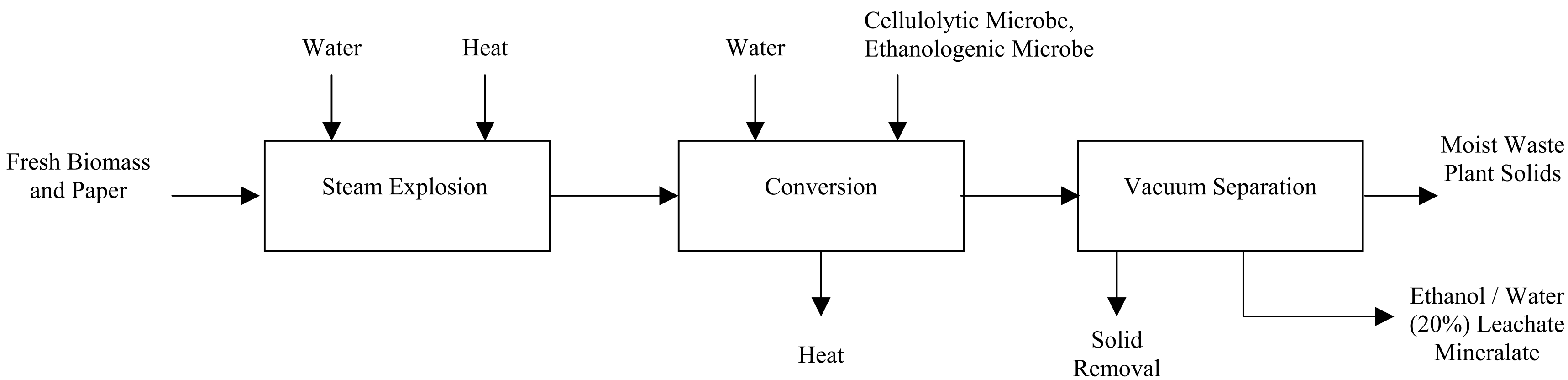
Paper and Biomass to Products

Figure 20: Paper and Biomass to Products Technology



TECHNOLOGY NAME/TYPE: **Paper and Biomass to Products**

Figure 21: Flow Diagram of Processes in Paper and Biomass to Products Technology



(1) Flash Process;
4 MPa at 200 °C

Alternatively, Acid Hydrolysis using Dilute Acid,
0.2 M H_2SO_4 at ~150 °C

(2) Microbe Control Product
(2a) Add Enzyme
➔ yeast – beer
(2b) Add Enzyme
➔ Single Cell Protein (SCP) yeast; Remove solids using centrifugation or metal filter
(2c) May share process equipment with food processing fermentation system
(2d) May require buffering or neutralization

(3) Ethanol vacuum distillation and condensation
(3a) Perhaps vacuum distill directly on conversion stage
(3b) Single Cell Proteins use centrifuge

TECHNOLOGY NAME/TYPE: **Paper and Biomass to Products**

MAJOR REACTIONS:
$CH_2O) \Rightarrow C_2H_5OH + CO_2$
$(CH_2O) \Rightarrow$ Biomass (microbial)
Fermentation products could be ethanol, single cell protein, vitamins, and/or organic acids.

SIDE REACTIONS:
Extractable nitrates?
N $\Rightarrow$ Biomass protein

RATE EXPRESSION (IF POSSIBLE):
$dM/dt = k\ (m - m_e)$
Ethanol = y x ΔM

TYPE OF FEED PREPARATION REQUIRED:
Size reduction to less than 1 cm

FEED RATE (kg/hr):
6.6 kg/day

TYPE CATALYST/ORGANISMS REQUIRED*:*
1 mg of microbes per kg of waste

PROHIBITED WASTES:
Biotoxins and human waste

TECHNOLOGY NAME/TYPE: **Paper and Biomass to Products**

Table 98: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Plant Matter, Waste Paper at 6.6 kg/day	Water, 10/1	1.5/1.0	40	I) 200°C II) 30°C	I) 170-240°C II) 25-37°C	I) 3-4.5 MPa II) 100kPa	I) 4 MPa II) ambient	48	8-96	I) Steam Explosion Step II) Conversion Step Depolymerization-hydrolysis stage-time dependent on pressure
*Added reactant would be any consumable (O_2, Air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported

EQUIPMENT/HARDWARE DATA

Table 99: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Pressure vessel, flash valve, and heater	?	3-5 $\times 10^{-3}$			Steel pressure vessel with a plunger to remove steam during purges or to place/remove solid waste materials Basis: Batch Process with 1 kg of waste per batch
2	Ambient fermentor and external pump		5L	low	low	Plastic or steel
3	Condenser					
4	Vacuum source					
5	Solid separation centrifuge or porous metal filter					
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Paper and Biomass to Products**

Table 100: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1			1/1	?	$X^{1.5}$	X^1	X = batch size; scale to feed rate

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume (see Note and Example on page 2 of Instructions for Scaling Factors).
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
None reported.

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
1) The ability to remove carbon dioxide in a microgravity environment (Scenario 1).

2) If only wastepaper is available (Scenario 2), “N” microbial nutrients will be required.

3) The other scenarios (Scenarios 4 and 5) will just increase the equipment scale presented here for Scenario 3.

TECHNOLOGY NAME/TYPE: **Paper and Biomass to Products**

Table 101: PERTINENT CRITERIA/ISSUES:

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	See prior remarks on carbon dioxide removal in microgravity.
Pretreatment Issues	Size reduction
Post Treatment Issues	May need additional distillation steps to prepare ethanol for potable use.
Safety	Batch steam unit; High pressure
Material	Fermentor/condenser could be fabricated from lightweight plastic.
Environmental Issues	
Reliability	This process is reliable in a batch mode, but yields vary at present – 5%
Integration:Technology Interactions	Partially digested solids need treatment; carbon dioxide release
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	2 – 3
Estimated Cost of Development to TRL of 5	2 – 4 years with 2 – 3 Equivalent People (EP) per year for the first products, and 2 years and 1 EP/yr for other products
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

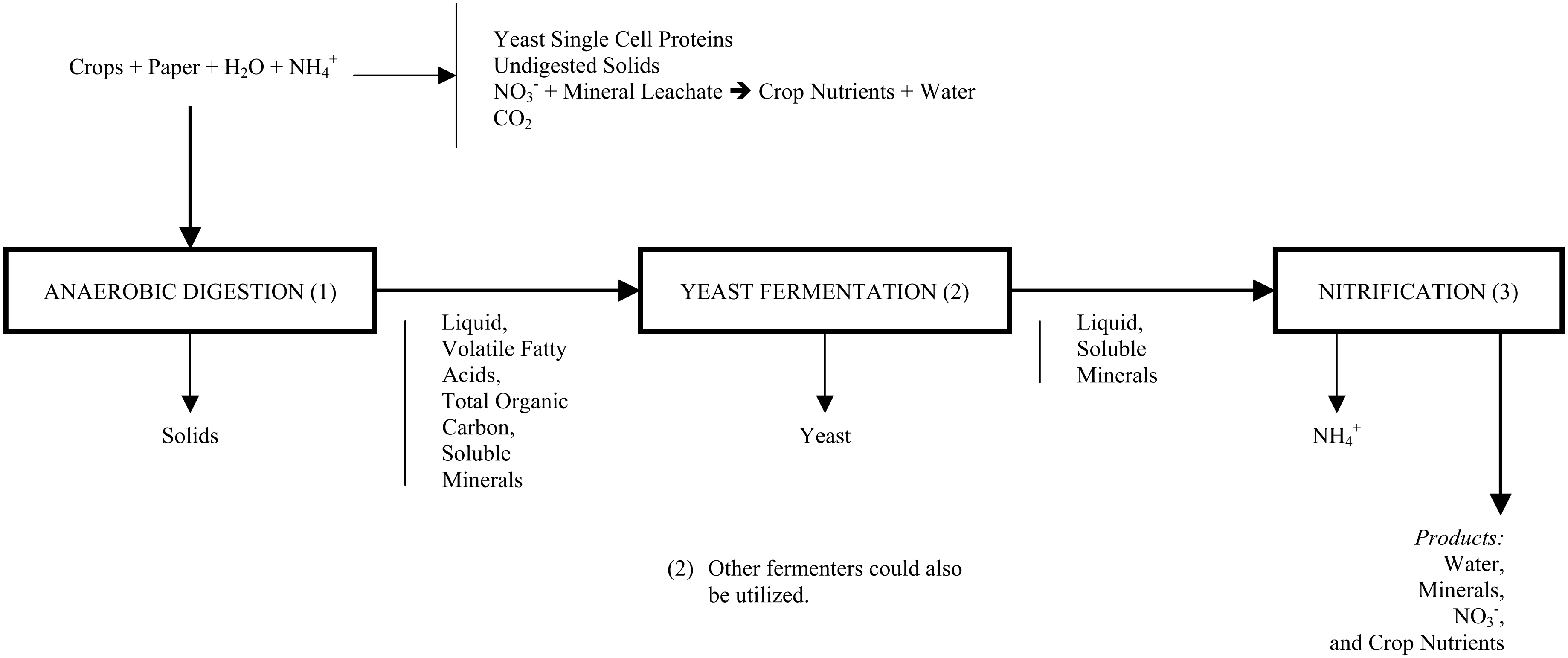
1) What other alternate technologies are comparable to this one?

2) What other type of technologies would help improve this one?
Gas separation for fermentor

3) What other types of work are currently going on to improve this technology?
Many projects are in progress in the renewable and agriculture industries, U.S. Department of Energy and Department of Agriculture.

Single Cell Protein Production and Crop Nutrient Recovery

Figure 22: Flow Diagram of Single Cell Protein Production and Crop Nutrient Recovery Technology



TECHNOLOGY NAME/TYPE: **Single Cell Protein Production and Crop Nutrient Recovery**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
(1) Anaerobic Digester Biomass ➔ CO_2 + Volatile Fatty Acids (VFA)
(2) Yeast Fermenters Volatile Fatty Acids ➔ Yeast single cell protein (SCP)
(3) Nitrification $NH_3 + O_2$ ➔ NO_3^-

SIDE REACTIONS:
Leach soluble minerals to recycle
Nitrate ➔ $NH_4^+ + O_2$ ➔ NO_3^- with losses

RATE EXPRESSION (IF POSSIBLE):
None recorded

TYPE OF FEED PREPARATION REQUIRED:
Size Reduction. See Strayer (1997) *Advances in Space Research*, **20**, pp. 2009-2015.

FEED RATE (kg/hr):
5.5 kg/day
For 25 g dry weight/day, volume (1) is 4 L, volume (2) is 2 L, and volume (3) is 0.5 L.

Overall: 25 g dry weight/day per 7 L (total system volume)

For 5.5 kg/day plant biomass, volume (1) is 700 L, volume (2) is 440 L, and volume (3) is 110 L.
For 33% conversion, 3.7 kg solids/day, 8% yeast, 0.5 kg yeast protein/day
1.3 kg solids ➔ 1.9 kg CO_2
Initial Nitrogen < 0.05 N Wt%
~50% converted NH_4^+ ➔ NO_3^- estimated, 0.1 kg O_2/5.5 kg

TYPE CATALYST/ORGANISMS REQUIRED:
Yeast: ~1 mg/kg_{waste}

PROHIBITED WASTES:
Biotoxins

TECHNOLOGY NAME/TYPE: **Single Cell Protein Production and Crop Nutrient Recovery**

Table 102: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Plants	Air 0.0202/1	3.7/0.577	33	300	285-320	100	50-150	10 days	6-15 days	Excess air ~10
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

EQUIPMENT/HARDWARE DATA

Table 103: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Anaerobic Digester	50	0.9	none	n/a	n/a
2	Yeast Fermenter	25	0.4			Replaceable part: Mixing
3	Fixed Film Reactor	5	0.1			Replaceable part: Cylinder
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR:
None reported.

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3: None reported.

TECHNOLOGY NAME/TYPE: **Single Cell Protein Production and Crop Nutrient Recovery**

Table 104: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Reactor (2) – Carbon dioxide removal
Pretreatment Issues	
Post Treatment Issues	
Safety	
Material	
Environmental Issues	
Reliability	Weeks of integrated testing
Integration:Technology Interactions	
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	3
Estimated Cost of Development to TRL of 5	Four equivalent people (EP) over three years.
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

1) What other alternate technologies are comparable to this one?
In food single cell protein production
The ethanol could be modified

2) What other type of technologies would help improve this one?
Increased plant biomass digestibility

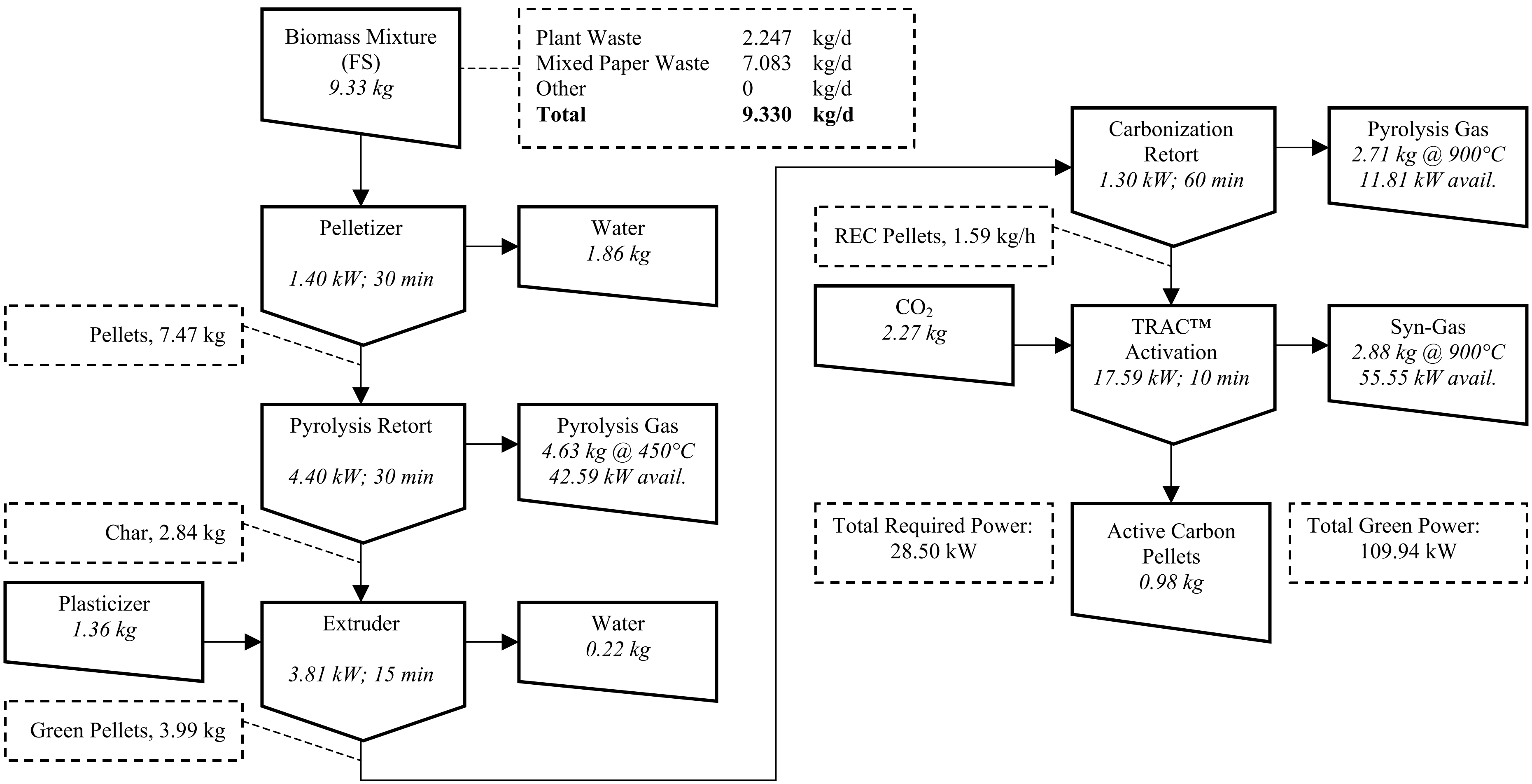
3) What other types of work are currently going on to improve this technology?

TECHNOLOGY ASSESSMENTS: PHYSICOCHEMICAL PROCESSING

This section contains raw data collected on thirteen different physicochemical processing technologies. The information contained in the following pages should be used, as starting point to gain basic understanding of the physicochemical technologies as related to future human space missions. What technologies are actually needed will depend on requirements, many of which have not been defined to this point. Waste processing requirements have been shown to be highly dependent on mission, configuration, and the types of wastes generated. For the summarized results on physicochemical technologies please consult Volume I, Section 4.3, of the workshop report.

Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process

Figure 23: Flow Diagram of TRAC™ Process Technology



TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

PROCESS DATA (NOMINAL & RANGES)

Figure 23 is the TRAC™ Process Flow Diagram (Batch Mode). Model: NASA 6-Person Crew using Scenario 3. Note: Calculated yields and caloric values are based on small-scale testing of similar biomass activation, 1999. Assumed Total Average Processing Time is 3 hours for this batch process.

Figure 24 shows schematically the feedstock preparation process through charring and char pelletization. Feedstock streams F1 and F2 (1) enter shredder (2) and are pelletized in a mill (4), where water (6) is extracted into reservoir (10). Extruded pellets (5) enter pyrolysis reactor (7) and are charred at relatively low temperature, over about 30 minutes. The gaseous volatiles (9) generated in the pyrolysis process (of which about 60% are condensable), enter a cyclone (11) for particulate removal, and continue in stream "F" to the catalytic cracker, shown in Figure 25. The solid char (8) obtained is in the form of flake and is taken through a quencher and cooler (13); the low temperature char (14) is then moved into a grinder (15) and then into a mixing extruder (17), where the plasticizer (16) is mixed in. The resulting "green" pellets are at elevated temperature, shown as stream "A," and are ready to carbonize.

Figure 25 describes the TRAC™ process schematically. "Green" pellets (1) enter in stream "A" from the extruder, and enter the retort (2) where the pellets are gradually heated (about 60 minutes) close to the activation temperature, under inert atmosphere, with the objective of driving off residual HC volatiles, leaving hard solid carbon matrix. The volatile gas driven off (3) is passed through cyclone (6), then to a catalytic cracker (15) where CO and CH_4 are produced, a synthesis gas mixture (16). This gas mixture is then passed on to the catalytic combustor (12) that is fed by the blowers (11) and uses lean Fuel/Air mixtures. A heat exchanger or boiler (13) extracts heat from the combustor. The products of combustion (14), mostly N_2, H_2O and CO_2 are passed on in stream "C" to the CO_2 capture unit described in Figure 26. The TRAC™ reactor (5) is processing the carbonized pellet stream (10 minute residence time), and the activated pellets (8) are collected. The TRAC™ reactor is fed by cool CO_2 stream (9) through the blower (10); the blower delivers a CO_2 stream "B" from the calciner, shown in Figure 26. The gas generated during activation (7), which is mostly CO, is mixed with the remaining CO_2 and passed on to the combustor (12).

Figure 26 describes schematically a coupled CO_2 capture unit and calciner, using dolomite, $MgCa(CO_3)_2$. The combustion exhaust gas stream "C" is passed through the calcined stone bed (MgO.CaO), where the CO_2 is chemically absorbed to reproduce the dolomite in an exothermic reaction. The dolomite is passed (20) to the calciner (19) that, with external heat input, produces CO_2 from the dolomite. This high temperature CO_2 is passed through a heat exchanger (23) to reduce its temperature, as it enters the TRAC™ reactor in stream "B." The unused portion (24) of the CO_2 is passed to the stack, (22), along with the exhaust gas stream (21) which remains after CO_2 absorption in the capture unit.

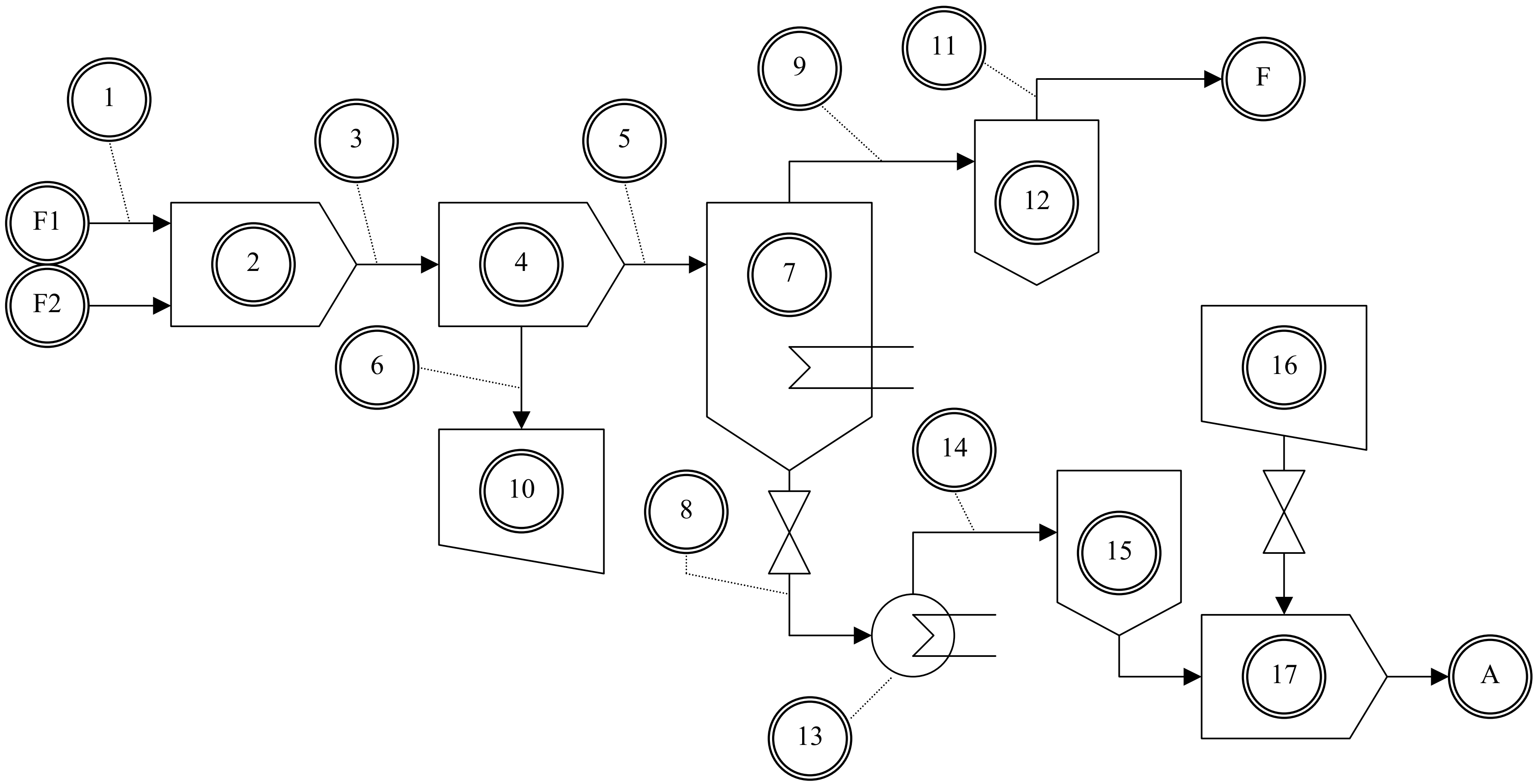
The technology: MBR Research's proprietary thermal rapid activation (TRAC™) technology processes cellulose-based char pellets into activated carbon. Typical activation times are 10 minutes, compared to 6-8 hours in conventional thermal activation, and the result in a pelletized product with BET surface area of 600 m^2/g to 1,300 m^2/g, with relatively high proportion of meso-pores (pore diameters between 20 and 200 Angstrom). A U.S. Patent was applied for in May 1999.

The complete processing cycle incorporates (1) feedstock pelletization, (2) charring, (3) grinding of the char, (4) extrusion of the char with a plasticizer/binder to form green pellets, (5) curing of these char pellets, and finally, (6) thermal activation under CO_2. The process elements are at near-atmospheric pressure, and at elevated temperatures.

Of the foregoing processes, pelletization, grinding and extrusion involve mechanical energy and are quite quantifiable. Pyrolysis, char pellet curing, and activation all require heat input, yet produce synthesis gas (of various composition and calorific content) with energy beyond the thermal requirements of the system. Note that processing on the order of 15 kg/day of waste by the crew, as described in NASA publication, would entail an overall batch process, where the mechanical power requirements could be readily satisfied by crewmembers in exercise mode. The thermal requirements would best be met by a highly compact, lightweight electrical system, which has been tested by MBR. The syn-gas may be utilized in several ways, e.g., direct energy (as in a lean-burning catalytic combustor) or for use in fuel cells (possibly methanation first, catalytically, using some hydrogen source).

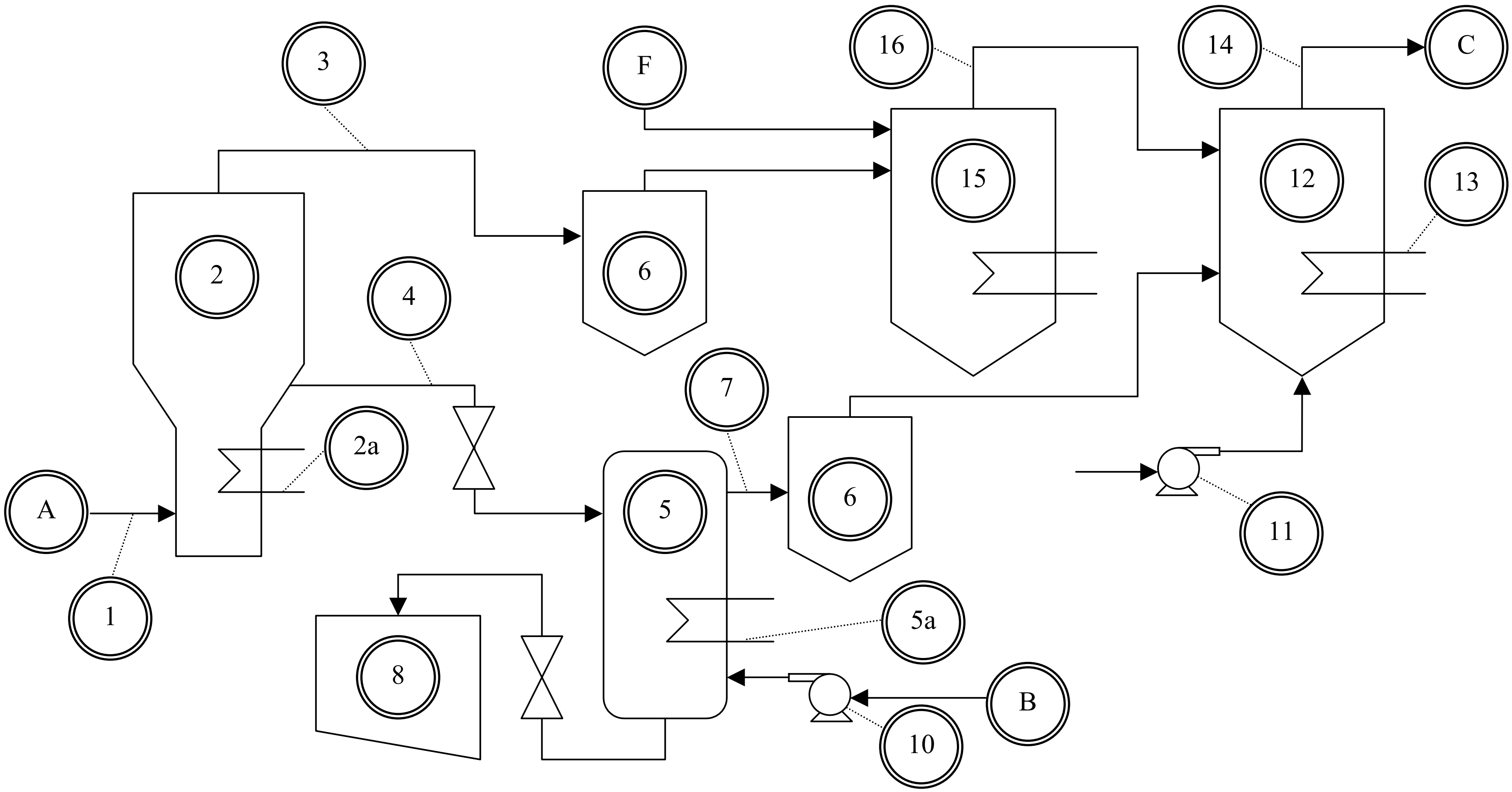
TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

Figure 24: Flow Diagram of Feedstock Stream Process of TRAC^{tM} Process Techn



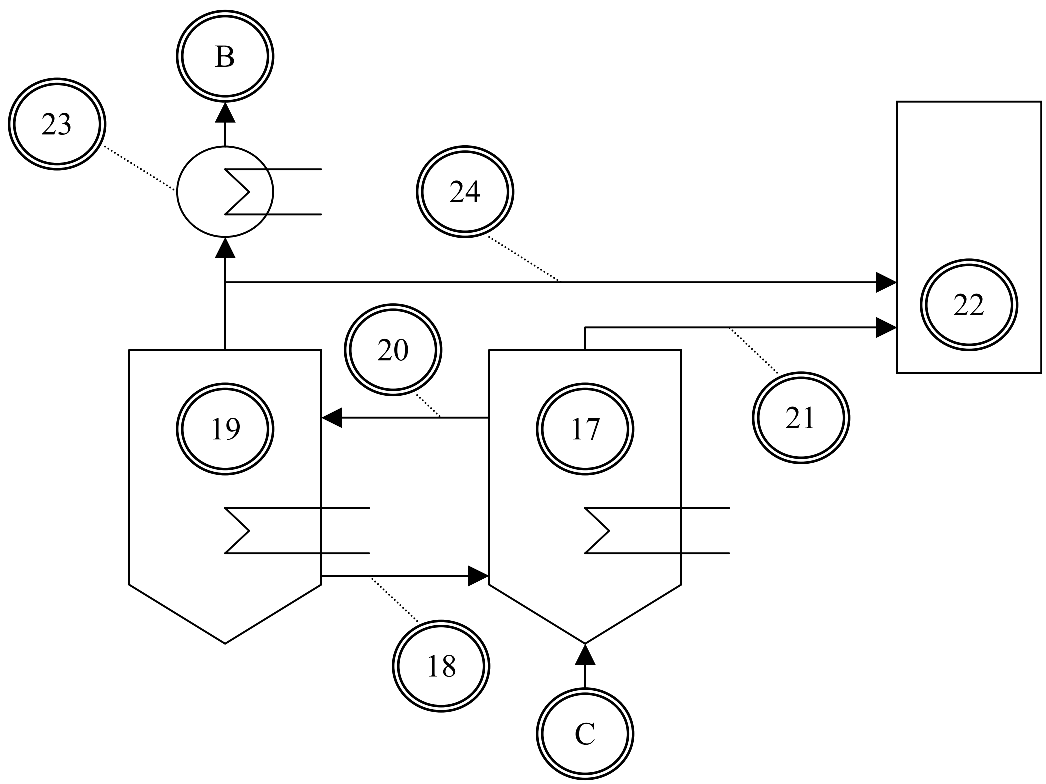
TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

Figure 25: Schematic Diagram of TRAC™ Process Technology



TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

Figure 26: Flow Diagram of Coupled CO_2 Capture Unit and Calciner



TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
(1) Pyrolysis: Chemical change occurs at the charring stages and at the thermal activation stage. The chemical reaction mechanism for pyrolysis of cellulosic materials has been suggested by Shafizadeh [12], and recast and summarized recently, e.g., by Mike Antal [13] of the University of Hawaii, and Christian Roy [14] of the University of Quebec.

(2) CO_2 Activation: The reactions associated with CO_2 activation of a carbonized char are, overall,

$$CO_2 + M \Rightarrow CO + O^* + M$$

$$R{-}C + O^* \Rightarrow R{-}CO^* \qquad \text{Where R - C denotes the carbonaceous aromatics}$$

$$R{-}CO^* \Rightarrow R^* + CO \qquad \text{Where R* denotes the activated carbon complex}$$

$$R{-}C + CO_2 \Rightarrow R^* + 2\,CO$$

The net process produces large amounts of CO, which serves as fuel. The process is endothermic, with an overall heat of reaction depending upon the extent of burn-off, or solid material oxidation. The complex pyrolysis process overall is thermally neutral, with material heat up serving as the major energy sink, while parts of the process are endothermic, and some other parts exothermic. Pyrolysis in charring occurs at about 400-500°C.

(3) Combustion of syn-gas (mostly CO, mixed with H_2, CH_4, CO_2 and H_2O) and the CO are normal oxidative reactions found in combustion literature, with mechanisms and kinetics documented. Of particular interest is CO combustion, which can be catalyzed (see C. Bruno, F. Bracco, et al. [15],), which will yield back the CO_2 with relatively small O_2 consumption. The overall reaction, $CO + 0.5\ O_2 + M \Rightarrow CO_2 + M$, is well documented, and its heat is - 67.35 kcal/mol (exothermic). Catalytic combustion can be done at low Fuel/Air ratios like 0.3, avoid NO_x formation, and at relatively low temperatures, e.g., 1,000 C.

(4) Calcination Reactions: These reactions concern the attachment of CO_2 to lime (exothermic), and then removal of CO_2 from dolomite by calcining, in the production/adsorption cycle. This process occurs at elevated temperatures, e.g., over 800ºC.

SIDE REACTIONS:
Only fully frontal reactions were considered.

RATE EXPRESSION (IF POSSIBLE):
No data is available for publication.

TYPE OF FEED PREPARATION REQUIRED:
See flow diagrams above and attached explanations.

FEED RATE (kg/hr):
Complete Processing of 15 kg of waste can be done within 3-4 hours overall. The activation step is only 10 minutes long. The average, overall processing rate is thus about 5 kg/hr. A daily batch process would be best suited for this purpose.

TYPE CATALYST/ORGANISMS REQUIRED:
The TRAC™ process is catalytic. However, there is no consumable catalyst involved.

TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

Table 105: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Combined Plant and Paper Wastes		19.9/80.1		325	300-600	15,000 †	10,000-25,000	30 min	20-40 min	Stage: Feed, Pelletization. This waste feed produces Feedstock Pellets; See next entry
Feedstock Pellets	Plasticizer; 48%	62.0/38.0		753	673-823	103	100-105	30 min	20-70 min	Stage: Charring Pyrolysis. This waste feed produces Char; See next entry
Solid Char		5.2/94.8		338	330-358	5,000	2,000-12,000	10 min	10-20 min	Stage: Char Pelletization. This waste feed produces Green Char Pellets See next entry
Green Char Pellets		60.0/40.0		1,173	800-1,200	103	100-105	60 min	30-70 min	Stage: Char Carbonization This waste feed produces Carbonized Pellets; See next entry
Carbonized Pellets	CO_2; 142.1%	74.7/25.3		1,173	1,100-1,200	103	100-105	10 min	5-15 min	Stage: TRAC™ Activation This waste feed produces Activated Carbon Pellets

* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.
† Note: This pressure applies to the solid-state pelletization process and it is not a gas pressure, nor is it a stored energy/safety issue.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

EQUIPMENT/HARDWARE DATA

Table 106: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power † (kW)	Heat Released † (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Biomass Pelletizer	9.33	0.0622	2	0	Component: TR-1 Replacement Parts: 0.311 kg/min; 2.07 L/min
2	Pyrolysis Retort	7.52	0.03419	5	42.9	Component: TR-2 Replacement Parts: 0.251 kg/min; 1.140 L/min
3	Char Pelletizer	4.23	0.01167	4	0	Component: TR-3 Replacement Parts: 0.282 kg/min; 0.778 L/min
4	Char Carbonization Retort	4.01	0.00526	2	11.9	Component: TR-4 Replacement Parts: 0.067 kg/min; 0.088 L/min
5	TRAC™ Activation Reactor	1.60	0.00292	18	55.9	Component: TR-5 Replacement Parts: 0.160 kg/min; 0.292 L/min
6	Dolomite Calciner/CO_2 Capture	n/a	n/a	n/a	n/a	Component: TR-6

1) Indicate if subassembly would need replacement at some other interval.
† Note: The power term is not continuous but related to the time duration outlined in Figure 23.

BACKGROUND OR REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR & MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

BACKGROUND OR REFERENCE INFORMATION:
The sizing is based on an existing unit. This unit can handle up to a maximum of about eight batches a day for eight times the rate. Therefore, scale up is highly nonlinear. It should not be scaled down however, because smaller units are not available, the overall size would actually decrease only in a minor way for smaller flow units, and the cost to develop smaller throughput units would be prohibitive.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Scenario 1: There are still materials, such as paper and biomass, that can be used to make activated carbon. The unit may be a bit oversized for the available feed. There are microgravity issues. Solids and gases have to be separated in several process units. There may also be some vapor-liquid separations. Other Scenarios: All other scenarios have adequate feed to make useful amounts of activated carbon.

TECHNOLOGY NAME/TYPE: **Activated Carbon and Energy from Cellulosic Waste By-Products using the TRAC™ Process**

Table 107: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Issues include solid-gas separation and vapor-liquid issues.
Pretreatment Issues	The low processing rates suggest possible use of direct manual labor, such as exercise cycle, for mixing and extrusions.
Post Treatment Issues	Pyrolysis gases and activation products must be oxidized.
Safety	1. The TRAC™ process has several high temperature components. 2. The generation of CO should be coupled to prompt combustion.
Material	Handles most of the wastes listed in NASA publication, excluding human waste. Materials of construction are conventional, such as stainless steel.
Environmental Issues	The resulting activated carbon material has a positive environmental impact, as it can be used for water or air purification.
Reliability	Very high
Integration:Technology Interactions	
Integration: Products of Process and their uses	The product activated carbon can be used for air and water clean up systems as well as contaminant control from waste processors.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 3. [The system has entered demonstration phase at full scale (100 kg/hour processing unit).] Development cost: $ 455,000.
Estimated Cost of Development to TRL of 5	$600,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	Approximately 6 months; $ 350,000
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

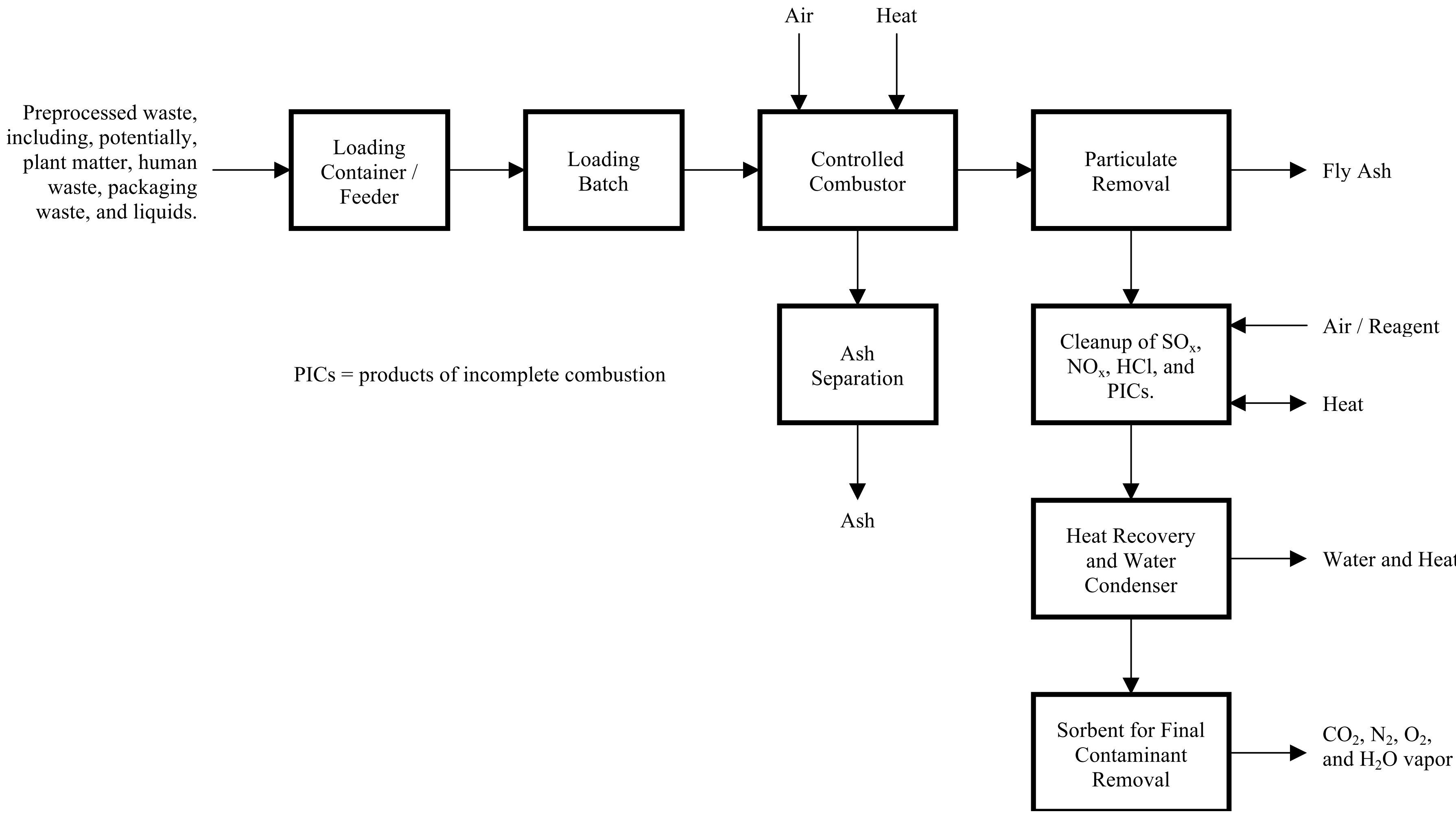
TECHNOLOGY ADVANCES:
1) What other alternate technologies are comparable to this one?
There are other ways to make char/activated carbon, but they are generally somewhat similar to this process.

2) What other type of technologies would help improve this one?
Solids conveyance, shredding, palletizing, and extrusion

3) What other types of work are currently going on to improve this technology?

Batch Incineration

Figure 27: Flow Diagram of Batch Incineration Technology



TECHNOLOGY NAME/TYPE: **Batch Incineration**

PROCESS DATA (NOMINAL & RANGES*)*

MAJOR REACTIONS:
Carbon + $O_2 \Rightarrow CO_2$
Hydrogen + $O_2 \Rightarrow H_2O$
Nitrogen in fuel + $O_2 \Rightarrow NO$
Sulfur + $O_2 \Rightarrow SO_2$

SIDE REACTIONS:
Formation of carbon monoxide
Formation of products from incomplete combustion, such as hydrocarbons, etc.
Formation of NO from reaction of nitrogen in the air
Formation of HCl from chlorinated compounds
Reduction reactions to destroy NO and oxidation reactions for total hydrocarbons (THC) and CO

RATE EXPRESSION (IF POSSIBLE):
Variable, but relatively rapid regardless of specific solid fuel when compared to other technologies. Pyrolysis and char oxidation data are available for a range of biomass fuel types.

TYPE OF FEED PREPARATION REQUIRED:
This depends upon the size of the unit, the burnout requirements, airflow rate, etc.

FEED RATE (kg/hr):
Same as above. The problem lies with a combination of storage, size of the unit, air requirements, etc. The more air that is available, the faster the waste burns. If the waste burns faster than the air is supplied, then pollutants will increase and affect the clean up system. If the bed becomes too hot due to temperature variations, then it may slag which in turn affects combustion and handling.

To design a system, one could assume a waste generation rate of 11 kg of waste over one day. Next, one sizes the duration for burning the prescribed daily waste loading, such as one hour.

TYPE CATALYST/ORGANISMS REQUIRED:
Oxidation and reduction catalysts, adsorbents for SO_2, polishing for total hydrocarbons, HCl, etc.

PROHIBITED WASTES:
Minimizing chlorinated solids helps with removing HCl. Trash containing trace metals, such as mercury, etc., should be avoided. These metals may vaporize, or vaporize and then condense, resulting in a higher concentrated fly ash.

TECHNOLOGY NAME/TYPE: **Batch Incineration**

Table 108: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Plant Wastes	O_2:C in a 1:1 or greater molar ratio	Ash	99% combustible; What remains is mostly ash	1,050	1,000 - 1,300	Variable In general, atmospheric		Depends	Minutes to Hours	Depends on size. Inorganic compounds may be recycled. Water may be removed by "drying" the feed at lower temperatures before increasing the temperature for combustion.
Human Wastes										Same as above; Ash recycling is unclear; Additional heat input is required.
Packaging										Similar; Additional heating value may be useful.
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
Microgravity would require a different design to contain the batches.
Scenarios 4 and 5 would have a much greater amount of biomass than in Scenario 3 and this is challenging because of its sheer size and associated heat release.
Biomass releases significantly more heat than other wastes.
Due to the differences in the scenarios, a phased system in terms of both type of incinerator and size might be better.

TECHNOLOGY NAME/TYPE: **Batch Incineration**

EQUIPMENT/HARDWARE DATA

Table 109: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Pre-treat and Load	Less than 65	Less than 0.4	Less than 1.5		
2	Incinerator	*	*	*	*	* Depends on size and heating value
3	Gas Cleanup Equipment					Depends, but the minimum life will be for the catalyst beds and heaters.
4	Ash Removal, Storage, and/or Recycle					
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
The workshop participants were not aware of a batch incineration system designed to NASA's specific issues. Without additional information on optimum size, specific cleanup issues, the above table is difficult to fill out. The batch pretreatment/loading will be simpler than for continuous modes. Waste removal will possibly be a challenge in reduced gravity environments.

MAJOR CONPONENT SCALING FACTOR:
None reported.

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
As discussed above, microgravity versus reduced gravity, differences in the types of waste (no biomass versus a large quantity of biomass), infrastructure available (for example, power), all lead to the conclusion that a phased effort should be explored. The effort could be phased in both the type of incineration system (for example, a simple batch system up to a complex continuous system) and size/capacity.

TECHNOLOGY NAME/TYPE: **Batch Incineration**

Table 110: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Please see above.
Pretreatment Issues	Some might be required.
Post Treatment Issues	Exhaust gas must meet requirements of growth chamber.
Safety	High temperature process
Material	Temperature limitations and corrosive nature of some components might require some material considerations.
Environmental Issues	Air must meet growth chamber requirements.
Reliability	Batch system might be simpler than continuous, which has potential for more reliability.
Integration:Technology Interactions	Plant growth technology; water treatment
Integration:Products of Process and their uses	Excess heat could be used; reuse of CO_2 and H_2O for plants; possible ash recycle for plants
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	2-3; Cost TBD
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY ADVANCES:

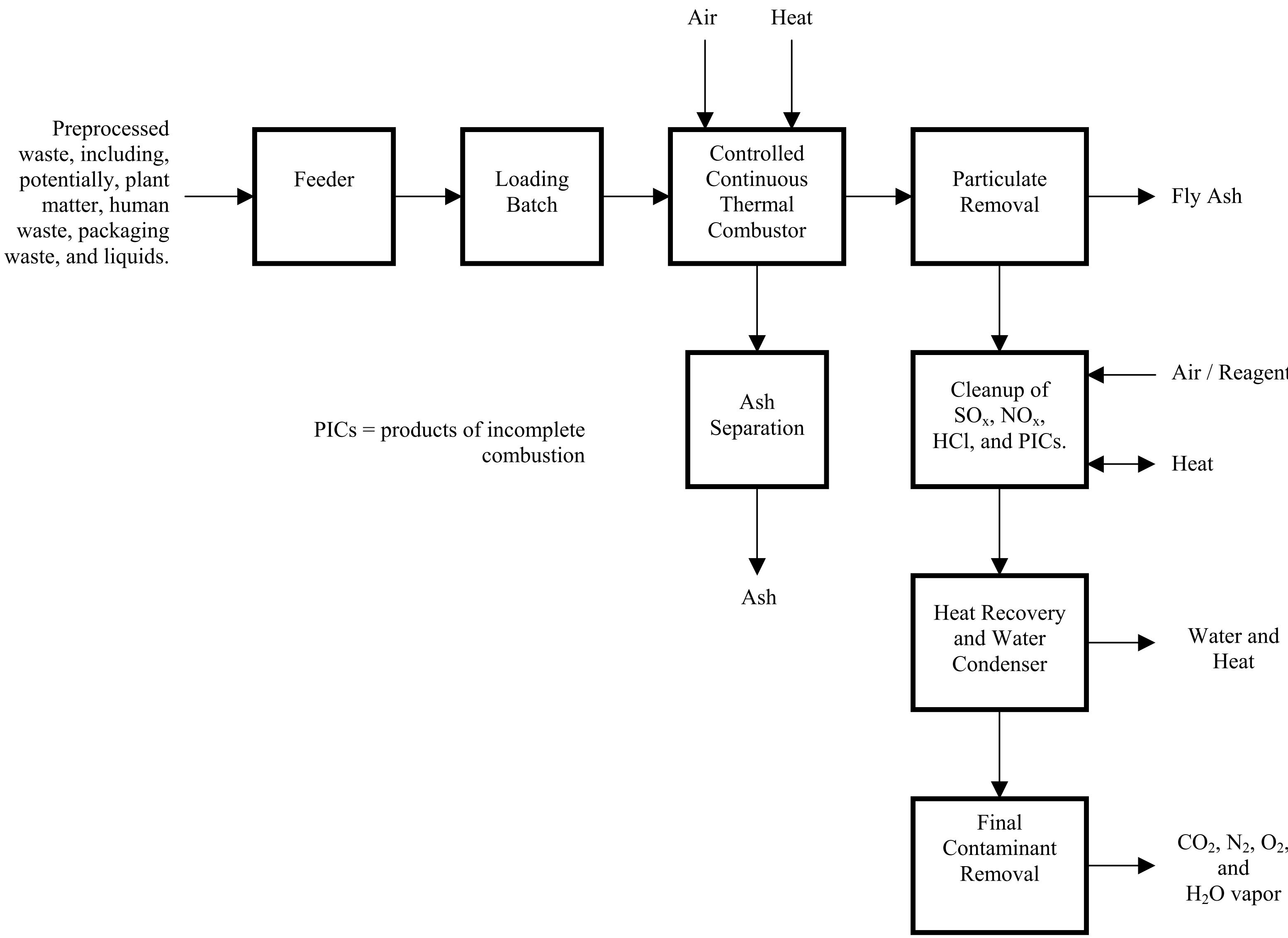
1) What other alternate technologies are comparable to this one?
This topic was discussed in the physicochemical area.

2) What other type of technologies would help improve this one?
Continuous development of reduction catalysts for off-gas cleanup. Combination of biological and incineration technologies might reduce the potassium and nitrogen which would aid in combustion and cleanup issues.

3) What other types of work are currently going on to improve this technology?

Continuous Thermal/Catalytic Incineration

Figure 28: Flow Diagram of /Catalytic Incineration Technology



TECHNOLOGY NAME/TYPE: **Continuous Thermal/Catalytic Incineration**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Solid Fuel + $O_2 \Rightarrow CO_2$, H_2O (CO and H_2 if temperatures low enough to prevent ash melting/reactions are maintained.)
$CO + {}^1/_2\, O_2 \Rightarrow CO_2$
$H_2 + {}^1/_2\, O_2 \Rightarrow H_2O$

SIDE REACTIONS:
Fuel N $\Rightarrow$ NO, N_2O, HCN and NH_3
Fuel S $\Rightarrow$ SO_2, H_2S
Fuel Cl $\Rightarrow$ HCl

RATE EXPRESSION (IF POSSIBLE):
Variable, but relatively rapid regardless of specific solid fuel when compared to other technologies
Pyrolysis and char oxidation data are available for a range of biomass fuel types.

TYPE OF FEED PREPARATION REQUIRED:
Plant Matter: Knife mill or otherwise reduce to a size which depends on approach, but is generally less than 10 mm for Fluidized Bed Combustion (FBC), or larger for Kiln or similar approach. Human Waste: Possibly some homogenization.

FEED RATE (kg/hr):
The feed rate is tied to the unit's size. Fluidized bed unit designed/built /tested by Reaction Engineering International and University of Utah typically operates at a few kg/hr. Higher temperature approaches that did not attempt to avoid ash melting/reaction could operate at much higher rates.

TYPE CATALYST/ORGANISMS REQUIRED:
A wide variety of both oxidation catalysts and reduction catalysts are available and have long enough lifetimes that the amount required per amount of feed is extremely small. Sorbents for removal of trace pollutants are required. However, under proper operational conditions the amount required is small.

PROHIBITED WASTES:
Chlorinated packaging is best avoided. Trash containing volatile toxic metals, such as mercury, are prohibited.

TECHNOLOGY NAME/TYPE: **Continuous Thermal/Catalytic Incineration**

Table 111: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Plant matter	Air in 5 to 20 % excess	Small amount of sorbent	>99% of combust.	1,050 1,300 K for conventional processes	1,000 - 1,250 1,250 - 1,500	116.3 In general, close to atmospheric	113 - 121	<<1		Inorganic material can be negatively affected in terms of further use, although preliminary evidence with FBC indicates much is soluble.
Human Waste										Similar, although additional heat input is required
Packaging										Similar, although potentially useful for heating value.
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
Much of the information in Table 111 pertains to the fluidized bed system at the University of Utah. Other incineration technologies are certainly applicable and would lead to different results. However, incineration, due to the relatively high temperatures involved, will be fast and complete. The impacts of the other scenarios on a fluidized bed process are:
Scenario 1: The added complication of reduced gravity clearly adds to the complexity of a fluidized bed system. For other approaches to incineration, the impact is likely minimal as long as forced draft systems are considered (buoyancy effects are negligible). The short duration and limited resource recovery make it difficult to justify complex systems.

Scenarios 2 and 3: Reduced gravity on Mars affects the design of a fluidized bed decreasing minimum fluidizing velocity and the reduced buoyancy must be considered for all high temperature systems.

Scenarios 3, 4, and 5: The increased reliance on recycling demands technologies that can effectively recover the carbon, hydrogen, and nutrients in a form useable for crop growth, making incineration increasingly attractive.

TECHNOLOGY NAME/TYPE: **Continuous Thermal/Catalytic Incineration**

EQUIPMENT/HARDWARE DATA

Table 112: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Knife Mill	65	0.366	1.5	0.2	Blades (Life: 120 hrs) Unnecessary for some approaches.
2	Dry Feeder	40	0.852	0.746	0.12	Teflon packing (Life: 200 hrs) Continuous processes tend to require more complex feeding.
3	Wet Feeder	34		0.519	0.1	Bed material (10 kg per 200 hrs); Heaters (Life: 4,380 hrs)
4	Incinerator	41	1.78	<2	6	
5	Gas Cleanup Equipment	123	1.53	1.8	0.7	Catalyst (Life: 22,000 hrs); Heaters (Life: 4,380 hrs)
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
The above values are for the Fluidized Bed Combustion system that is not optimized for mass, volume, or power. There is much room for improvement.
The above system was designed for a four-person crew, but it is already capable of handling a six-person stream. In general, other approaches will be of a similar order of magnitude.

MAJOR COMPONENT SCALING FACTOR:
None reported.

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Scenario 1: Microgravity can complicate the movement of any process stream including grinding, feeding, particulate and condensable collection.
Lack of gravity, limited nature of waste stream (smaller and primarily human waste in scenarios 1 and 2), lack of infrastructure development all lead to the conclusion that the use of more complex continuous processes are more justifiable in scenarios 3, 4, and 5; and phased use of batch/continuous systems are more desirable in earlier scenarios. In other words, a batch process should be used for scenarios 1 and 2, a continuous process in scenarios 4 and 5, transitioning in scenario 3.

TECHNOLOGY NAME/TYPE: **Continuous Thermal/Catalytic Incineration**

Table 113: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Fluidized bed designs are affected but can be designed to operate over a wide range. Other incineration approaches also need to consider the lack of buoyancy effects.
Pretreatment Issues	Variable depending upon specific approach (< 10 mm particle size for Fluidized Bed Combustion) Removal of alkali, chlorine, and water should be considered, but are not required.
Post Treatment Issues	Gas cleanup equipment is necessary for removal of pollutant species from heteroatoms in the feed and any products of incomplete combustion. Issues involving plant tolerances should be considered.
Safety	Damage to insulation protecting high-temperature surfaces must be avoided, common power requirements, and maintenance of gas cleanup equipment.
Material	Zirconia bed materials are necessary to avoid ash/bed material interactions. Appropriate high-temperature materials are required.
Environmental Issues	Dedicated cleanup equipment and trace contaminant control subsystem are necessary to prevent environmental contamination to humans and plants.
Reliability	Commercial development in terrestrial environments provides a strong base for technology reliability. Untested in low gravity
Integration: Technology Interactions	Could be used to assist in destruction of biological hazards. Incineration could be used in conjunction with biological processing as the strengths and weaknesses are complimentary.
Integration: Products of Process and their uses	CO_2 and potentially inorganic nutrients in ash can be used for crop growth. Could be used to provide heat.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	5; this technology benefits from decades of terrestrial research and University of Utah, Reaction Engineering International, and NASA Ames Research Center funds over last 6 yrs totaling <$1 million.
Estimated Cost of Development to TRL of 5	0
Estimated Time & Cost to Manufacture a Unit to TRL of 5	0
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See Figure 2 for TRL definitions.

TECHNOLOGY NAME/TYPE: **Continuous Thermal/Catalytic Incineration**

TECHNOLOGY ADVANCES:

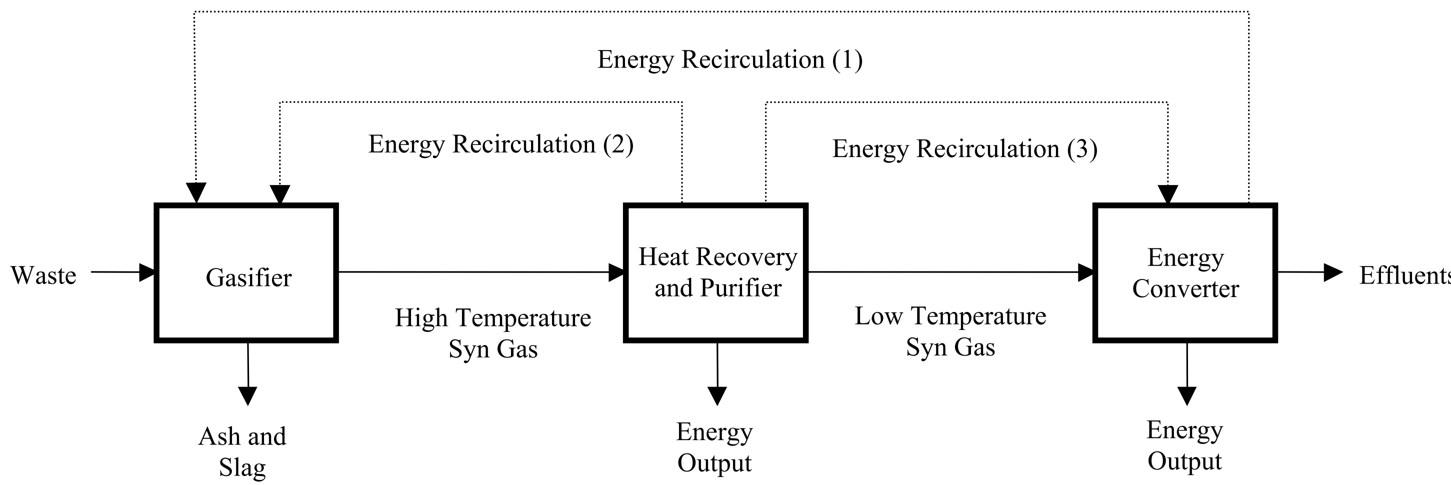
1) What other alternate technologies are comparable to this one?
Thermal/catalytic approaches involving continuous and batch techniques have been considered.
Several physicochemical processes are comparable.

2) What other type of technologies would help improve this one?
Continued development of reduction catalysts with emphasis on ammonia destruction.
Design of milling and feeding systems with emphasis on reducing size and weight.
Design using a combination of biological and incineration technologies. For example, pretreatment of waste using biological approaches to remove a significant amount of alkali will simplify combustion systems and improve lifetime and reliability, while the difficulties of completely and quickly processing organic components of the waste with biological techniques are avoided.

3) What other types of work are currently going on to improve this technology?
There is much room for improvement in terms of size, weight and power.

High Temperature Gasification

Figure 29: Flow Diagram of High Temperature Gasification Technology



TECHNOLOGY NAME/TYPE: **High Temperature Gasification**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
The pertinent chemical reactions for High Temperature Air Gasification:
Carbon/Hydrocarbon + O_2 + N_2 (-Q_1 out, Exothermic Reaction) $\Rightarrow$ $CO + CO_2 + H_2 + H_2O + N_2$

High Temperature Steam Reforming Reactions:
Carbon/Hydrocarbon + H_2O (steam) (+Q_2 in, Endothermic Reaction) $\Rightarrow$ $CO + H_2$

Overall:
Solid Fuel + Heat (+ Steam) $\Rightarrow$ $CO + CO_2 + H_2 + \ldots$ (Energy)

SIDE REACTIONS:
Not precisely known.

RATE EXPRESSION (IF POSSIBLE):
High-temperature chemistry and reactions not known

TYPE OF FEED PREPARATION REQUIRED:
No preparation is required. Smaller sized particles are preferred.

FEED RATE (kg/hr):
~10 to 20 kg/hr, based on the waste model

TYPE CATALYST/ORGANISMS REQUIRED:
Not applicable.

PROHIBITED WASTES:
Not applicable.

TECHNOLOGY NAME/TYPE: **High Temperature Gasification**

Table 114: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Solid Waste	Initial thermal energy is required for heat-up, such as gas or liquid fuel.	Only the inorganic portion of the waste stream (ash)	>99%	1,200 °C (1,500K)	1,000 – 1,400 °C (1,300 – 1,700K)	101		A function of the waste composition	~ seconds to minutes	Refer to Process Flow Diagram.
Air	Stoichio-metric Air									
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

EQUIPMENT/HARDWARE DATA

Table 115: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	High Temperature Air	TBD	0.2 – 0.4	None	TBD	
2	Gasifier Chamber	TBD			Function of waste properties	Ceramic balls, an expendable, may be needed for the Gasifier. Rate: A few per week.
3	Heat Recovery Unit	TBD				
4	Chemical to Thermal Energy Converter	TBD				
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported

TECHNOLOGY NAME/TYPE: **High Temperature Gasification**

EQUIPMENT/HARDWARE DATA

Table 116: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1		X	X				The scaling factor depends upon the residence time of the material that, in turn, depends upon the material particle size.

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 117: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Gasifier					

1) Indicate if subassembly would need replacement at some other interval.

BACKGROUND/REFERENCE INFORMATION:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Similar to Scenario 3 except for the concentrated liquid waste feed

TECHNOLOGY NAME/TYPE: **High Temperature Gasification**

Table 118: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	No data is available for microgravity and hypogravity environments. Performance of this technology should be better in a microgravity environment.
Pretreatment Issues	Reduction of waste to smaller size is preferable, but <u>not</u> necessary.
Post Treatment Issues	Gas cleanup will be required. No problems with Dioxins under 1-g.
Safety	Closed system. Insulation provides better performance.
Material	Use of high-temperature materials for operations at 1,100 to 1,400 °C.
Environmental Issues	Environmentally benign.
Reliability	Very reliable.
Integration:Technology Interactions	Some of the information available on pyrolysis and gasification from other technologies can be used here.
Integration:Products of Process and their uses	The slag from this technology may not be processed by leaching.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	2
Estimated Cost of Development to TRL of 5	Cost of gas treatment system integration and optimization
Estimated Time & Cost to Manufacture a Unit to TRL of 5	Research and development is necessary. Costs associated with reaching a TRL of 5 are given above.
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) <u>Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.</u> 3) See Figure 2 for TRL definitions.	

TECHNOLOGY ADVANCES:

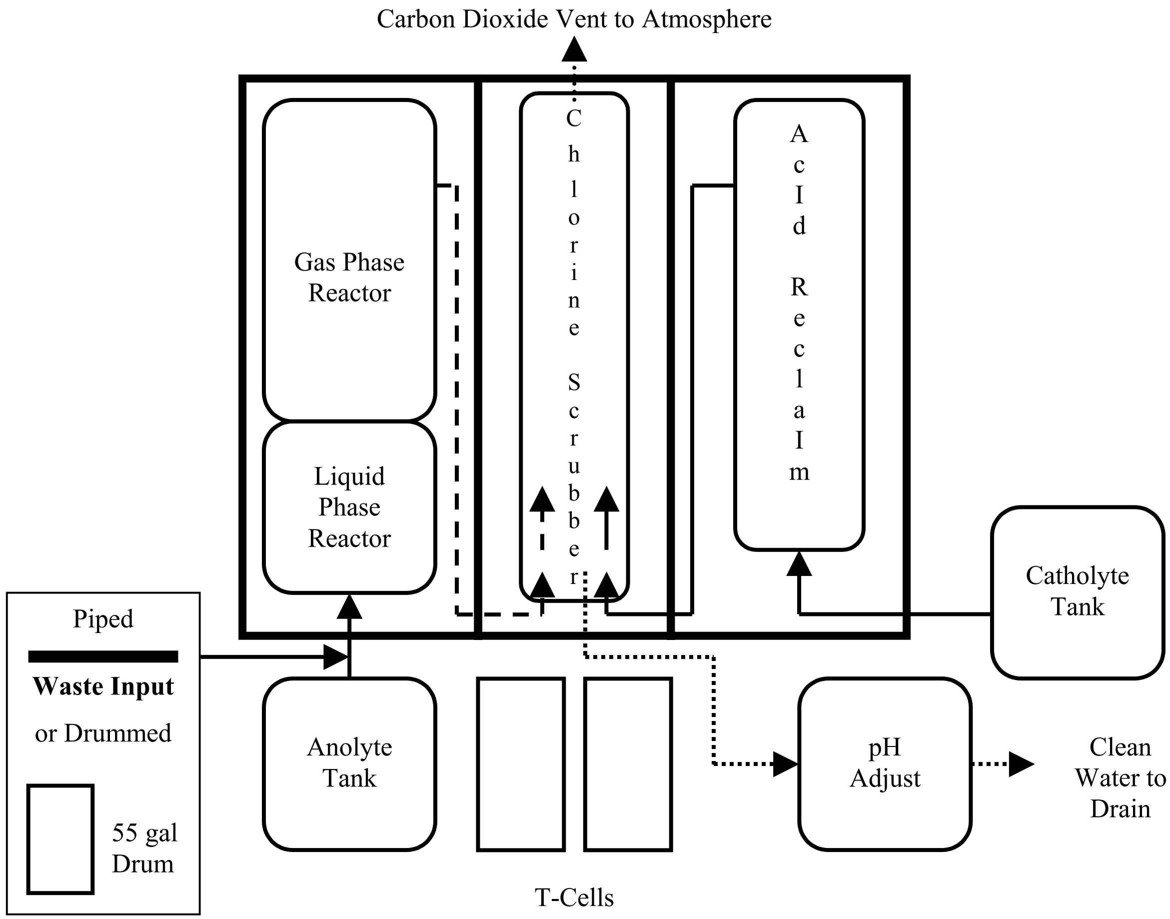
1) What other alternate technologies are comparable to this one?
Energy recovered from wastes is used to gasify the waste stream.
Comparable technologies: Pyrolysis and Gasification
Magnetically Activated Gasification

2) What other type of technologies would help improve this one?
Pyrolysis, gasification, and fuel reforming

3) What other types of work are currently going on to improve this technology?
Slagging in the gasifier
Data on trace gases in effluents
Efficient energy conversion and heat exchange from wastes recirculated back to the gasifier
Use of steam for steam reforming

Indirect Electrochemical Oxidation

Figure 30: Schematic of CerOx System 4 Technology as Commercialized by CerOx Corporation



TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

PROCESS DATA (NOMINAL & RANGES)

(Ce^{3+}/Ce^{4+} Redox Couple Used as Example Here)

Indirect electrochemical oxidation encompasses all those processes in which the pollutant is indirectly oxidized, either by generation of oxidants (e.g., Cl_2, ClO^-, H_2O_2, O_3) or by presence of a redox couple (Ag^+/Ag^{2+}, Fe^{2+}/Fe^{3+}, Co^{2+}/Co^{3+}, Ce^{3+}/Ce^{4+}) that is used as an electron carrier for oxidation. The process description that follows is based on a Ce^{3+}/Ce^{4+} redox couple system that has been tested at pilot scale level. A copy of the CEROX Equipment and Technology Process is attached to the end of this report. The readers of this report should consult the following references – Rajeshwar [16], Sequeira [17], and Tatapudi [18].

The active Ce(IV) oxidant is produced in the T-CELL, a plate and frame electrochemical cell designed by the CerOx Corp. This cell is coupled to the main electrolyte pumps and to the electrolyte storage tanks, forming the anolyte system. The CerOx System 4 has an electrolyte circulation rate for the anolyte and catholyte of about 80 gallons per minute each. These separate flows are balanced to minimize any pressure differential across the Nafion® membranes. The catholyte tank is constructed of stainless steel and holds about 70 gallons of 20% nitric acid. The anolyte tank is constructed of titanium and holds about 70 gallons of anolyte, 1.5M cerium nitrate dissolved in 20% nitric acid.

The organic destruction occurs in a tandem set of reactor vessels, both constructed of titanium. The organic waste materials are metered into the liquid phase reactor through an ultrasonic mixer, of CerOx Corp. design, which emulsifies the materials to maximize the waste contact area with the Ce(IV) solution. The organic materials react with Ce(IV) to produce (mostly) carbon dioxide and, if chlorocarbons are present, chlorine gas. The gaseous products are vented through the second packed bed reactor in which the exhaust gases are contacted with a countercurrent flow of Ce(IV) anolyte. This reactor is designed to destroy any adventitious volatile organic carbon materials that may have been volatilized from low boiling materials in the liquid phase reactor.

The destruction process is controlled by metering the addition of the waste materials, matching the organic content to the Ce(IV) consumption within the reactor to preset limits, typically a set point for the decrease in Ce(IV) over the reactor between 0.3M to 0.5M that is operator-selectable for the optimum set point control differential. The addition rate of the organic is controlled by monitoring the Ce(IV) concentration difference between the entering and exiting process streams of the liquid phase reactor and using this difference signal to control the rate of organic addition to maintain the desired Ce(IV) level in the reactor.

The cathode reaction is the reduction of nitric acid at the cathode. This process produces nitrous acid and water that requires the acid recovery unit operation to remove water and recover nitric acid. Water is removed using direct condensation or with a vacuum evaporator. The nitric acid is recovered through oxidation of the catholyte off-gas, with molecular oxygen or air, followed by absorption of the nitrogen oxides to recover the nitric acid.

The final subunit is the scrubber component for chlorine removal from the reactor exhaust gas. Chlorine (Cl_2) arises from reaction of any chlorine contained in the incoming waste stream. This includes any carbon bound chlorine found in chlorocarbons such as trichloroethylene (TCE) or inorganic chlorine compounds such as hydrochloric acid. The scrubber removes the chlorine by dissolution in water and subsequent neutralization with sodium hydroxide. The scrubber also is used to neutralize the small amount of nitric acid in the reject water from the evaporator used on smaller on-site units, typically 0.04% acid, before this stream is sent to water treatment. Larger units will have a membrane-based acid recovery unit, similar to a reverse osmosis (RO) process, to recycle the acid content of this product water stream back to the system (see above Figure 30).

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Redox Reactor Reaction (reaction occurs in anolyte tank of Figure 30)
(Ce^{3+}/Ce^{4+} Redox Couple Used as Example Here)
Ce^{4+} + solid waste + $H_2O \Rightarrow CO_2 + H^+ + Ce^{3+}$
Using acetic acid as an example:
$12\ Ce^{4+} + CH_3CO_2H + H_2O \Rightarrow 2\ CO_2 + 12\ H^+ + 12\ Ce^{3+}$

Anodic Reaction of Regenerative Electrochemical Cell
$Ce^{3+} \Rightarrow Ce^{4+} + e^-$
$2H_2O \Rightarrow O_2 + 4H^+ + 4e^-$

Cathode Reaction of Regenerative Electrochemical Cell
$HNO_3 + 2H^+ + 2\ e^- \Rightarrow HNO_2 + H_2O$
$2H^+ + 2\ e^- \Rightarrow H_2\ (g)$

SIDE REACTIONS:
Reactions with acid form inorganic compounds from the related acid. In other words, chlorine arises from hydrochloric acid, nitrogen arises from nitric acid, sulfur arises from sulfuric acid, and phosphorous arises from phosphoric acid.

Reactions with metals form oxides. Cerium leads to cerium oxide. Other metals, such as Zn, Cd, Ni, Cr, Pb, Ag, and Hg, exit the reaction as metal, metal oxide or dissolved as metal ions.

RATE EXPRESSION (IF POSSIBLE):
Detailed rate expressions are not available but pilot scale results are available and empirical reaction rates are available. The attached report provides some of this information.

TYPE OF FEED PREPARATION REQUIRED:
Size reduced to allow pumping and efficient oxidation in reactor vessel desired but not required. The reaction rate is a strong function of the access of Ce^{4+} to the solid waste. 10 micron or less in size would be preferred. Can tolerate a wide range of solids 2% to 50%.

FEED RATE (kg/hr):
A wide range of feed rates is possible. The electrochemical redox regeneration reactor scales with area of electrode. The solid waste Ce^{4+} reactor scales with the volume. This process scales down very well. The presented example is based on 55 gallons of liquid organic waste per day.

RHEOLOGY:
A wide range of physical forms and chemical compositions are possible.

TYPE CATALYST/ORGANISMS REQUIRED:
Dissolved redox couple Ce^{3+}/Ce^{4+}

PROHIBITED WASTES:
None. Volatile feeds that may not be soluble in the aqueous redox couple reactor solution may end up in the off gas.

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

Table 119: PROCESS DATA

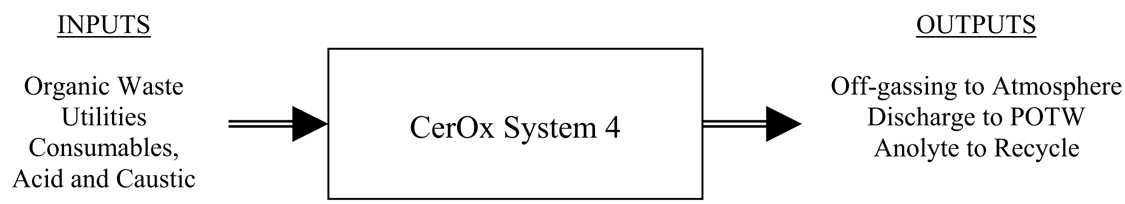
Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Inedible plant biomass	0	1:10	90%	370	+/- 50	101		variable	variable	Residence times are proportional to volume of the oxidation Ce^{4+} reactor
Dry Human waste	0	5:100	95%	370	+/- 50	101		variable	variable	
Trash	0	4:10	60%	370	+/- 50	101		variable	variable	
Packaging material	0	2:10	80%	370	+/- 50	101		variable	variable	
Paper	0	1:10	90%	370	+/- 50	101		variable	variable	
Tape	unknown	unknown	unknown	370	+/- 50	101		unknown	unknown	
Filters	unknown	unknown	unknown	370	+/- 50	101		unknown	unknown	
Miscellaneous	unknown	unknown	unknown	370	+/- 50	101		unknown	unknown	
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
Since both the electrochemical redox reactor and the Ce^{4+} oxidation reactor are all solid/liquid systems, gravity is not a difficult issue. The chlorine scrubber does not require gas/liquid contacting. Reoxidizing HNO_2 back to HNO_3 in the acid recovery unit involves contact with oxygen. It may be best to substitute the HNO_3 electrochemical reduction with the direct reduction of water to form H_2 (gas).

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

PROCESS DATA (NOMINAL & RANGES)

Figure 31: Inputs and Outputs for CerOx System



A. CerOx System 4 Inputs:

Utilities:
Industrial water: 1.5 gallons per minute used for operation of the post-reaction gas scrubber.
Electricity: Approximate usage is 90 kVA.

Consumables:
Oxygen or air: 2 standard ft^3/min (scfm) or equivalent in air (10 scfm).
Nitric acid (42° Baume): Approximately 4 lb_m/hr during operation.
Sodium hydroxide (50% Solution): 2 lb_m/hr of operation for nitric acid neutralization. 2.25 lb_m per lb_m chlorine in input waste stream.

B. CerOx System 4 Outputs

Releases to the POTW:
1.5 gallons per minute of incoming industrial water, pH adjusted with sodium hydroxide (1.8 lb_m dissolved chlorine containing salts per lb_m of chlorine in the incoming waste stream). 5 gallons per hour of 0.04% nitric acid, neutralized with sodium hydroxide (0.02 lb_m/hr of $NaNO_3$ in the discharge).

Anolyte Recovery/Recycle:
Used anolyte containing 4 lb_m/gal of cerium nitrate ($Ce(NO_3)_3$) and 1.6 lb_m/gal of nitric acid. This solution is sent off-site for cerium and nitric acid recovery for recycle to the process.

Releases to the Atmosphere:
Scrubber exhaust volume of 50-60 scfm. Reactor exhaust of 15 - 25 scfm, predominantly CO_2, plus make-up air required to maintain a negative pressure in the exhaust system for efficient chlorine scrubbing.

Exhaust Gas Sources:
Many organic waste streams contain chlorine and nitrogen, while all contain oxygen (along with carbon and hydrogen) with varying amounts of water. Carbon is converted to CO_2, hydrogen to H_2O, chlorine to Cl_2, oxygen to water and nitrogen to nitric acid. The gaseous products, preponderantly CO_2 and Cl_2, are released from the reactor tanks and sent to the chlorine scrubber. (During process development in the national labs, it was found that production of CO_2 does not go through a carbon monoxide intermediate so there is very little CO present in the exhaust stream.)

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

Chlorine:
The carbon-bound chlorine contained in the organic waste materials is converted to gaseous chlorine (Cl_2) by the process. This mode of removal and rejection of chlorine from hazardous organo-chlorine waste materials allows for a simple separation and capture of this noxious component in organic waste streams. The removal and neutralization of chlorine is accomplished using a commercial, high efficiency, chlorine scrubber that is integrated into the CerOx System 4 unit. In fact, the design of CerOx System 4 unit requires that all gases released from any part of the unit pass through the scrubber before entry to the environment.

VOC:
The destruction process of the organic materials in the CerOx System 4 is a stepwise oxidation process for the organic materials. The organics are broken into progressively smaller pieces by exhaustive oxygenation to, finally, carbon dioxide. While the oxygenation process results in the formation of organic intermediates with low vapor pressure and high electrolyte solubility, the CerOx System 4 incorporates a proprietary reactor tank system designed to eliminate VOCs in the exhausting CO_2 stream before it is sent to the chlorine scrubber.

NO_x:
The cathode process used by the CerOx Corp. process technology involves the reduction of nitric acid to nitrous acid which can, in turn, disproportionate to NO and NO_2. The nitric acid is regenerated from these reduced nitrogen materials by re-oxidation with oxygen (or air) in an absorber column. The exhaust gases from the nitric acid recovery absorber unit on the catholyte loop and from the vacuum pump in the water evaporation/distillation unit are vented through the chlorine scrubber.

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

Table 120: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Electrochemical Cell	300	0.6	15		
2	Anolyte Tank/Pump	430	0.6	1		Unknown systems do not have enough field deployed experience to make good estimates.
3	Catholyte Tank/Pump	430	0.6	1		
4	Cerium Reaction Tank	430	0.6	1		
5	Acid Recovery System	430	0.6	1		
6	Chlorine Scrubber	430	0.6	1		
7	NaOH Storage	200	0.3			
8	Controls, Piping, & support structure	660	1.2			
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION: Based on CerOx System 4 with 50 gallons per day capacity actual feed. Scaled for Scenario 3 producing an estimated 7 gallons per day feed at 40% organic solids and 60% water. Total amounts are known; at this time, the values listed above are best estimates on a percentage basis of the total.

Table 121: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	0.15	0.3	0.3				See comments below for explanation.
2	0.15	0.3	0.3				
3	0.15	0.3	0.3				
4	0.15	0.3	0.3				
5	0.15	0.3	0.3				
6	0.15	0.3	0.3				
7	0.15	0.3	0.3				
8	0.15	0.3	0.3				

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

BACKGROUND OR REFERENCE INFORMATION:
See attached CerOx data on System 4. This analysis is based on CerOx System 4 with 50 gallon per day capacity or 7x (required capacity) estimated at 7 gallons per day. Power consumption is estimated to vary linearly with feed rate or 0.15 of values provided in Table 162. Component size and mass estimated to be approximately 50% of components of CerOx System 4. This is due to manufacturability issues. Actual sizes for a dedicated NASA unit could probably be reduced further in size.

Table 122: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Industrial Water					0.6 to 0.9 L/min that is potentially recycled
2	Oxygen/Air					0.004 m^3 O_2 or 0.02 m^3 Air
3	Sodium Hydroxide (50% solution)					0.135 for Nitric Acid Neutralization
4	Sodium Hydroxide					2.75 gm/gm chlorine in waste feed
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND OR REFERENCE INFORMATION: None reported

Table 123: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	N/A	0.15	0.15				Process is essentially scaled linearly since process dynamics are linear for all power and consumables
2	N/A	0.15	0.15				
3	N/A	0.15	0.15				
4	N/A	0.15	0.15				
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND OR REFERENCE INFORMATION: None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3: None reported.

TECHNOLOGY NAME/TYPE: **Indirect Electrochemical Oxidation**

Table 124: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Waste decomposition gases and gases generated by electrolysis have to be separated from a liquid process stream.
Pretreatment Issues	Insufficient data is available on optimized pretreatment conditions for different waste feeds.
Post Treatment Issues	Types of waste gases generated and possible treatment methods are poorly understood.
Safety	Hazardous include caustic and/or acidic liquids and gases including pure oxygen.
Material	Limited test data and optimum materials. Very demanding operating environment. New specialized materials are needed.
Environmental Issues	
Reliability	High reliability is a significant challenge given the corrosive chemical environment.
Integration:Technology Interactions	While there are numerous subsystems used in the process, integration has already been performed and optimized.
Integration:Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	4 $650,000
Estimated Cost of Development to TRL of 5	$5,000,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	3 years $2,000,000
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY ADVANCES:

1) What other alternate technologies are comparable to this one?
Wet oxidation and super critical water oxidation

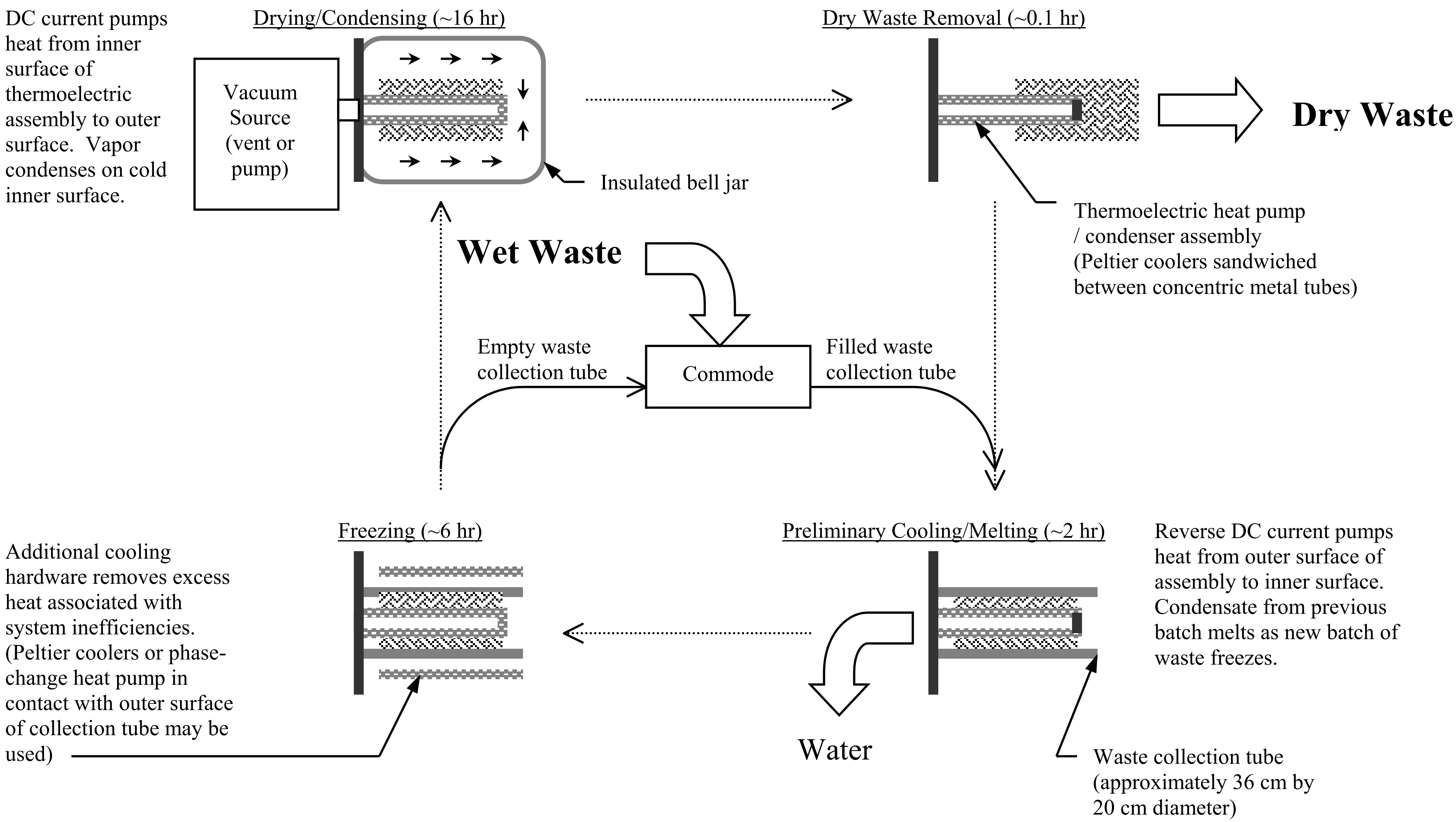
2) What other type of technologies would help improve this one?
Improved catalytic oxidation methods and effluent treatments for combustion gases

3) What other types of work are currently going on to improve this technology?
Materials research for reactor materials, electrode materials, and membranes. Various types of alternative oxidizing agents can be generated using this technology. Work on the use of redox couple oxidation or chemical oxidizing agent oxidation would impact the choice in the electrochemistry.

Technology Assessed by: Craig Hooper, Newport News Ship Building, (757) 688-0579
Jim Fenton, University of Connecticut, (860) 486-2490
Duncan Hines, Lynntech, (409) 693-0017

Lyophilization (Freeze Drying)

Figure 32: Flow Diagram of Lyophilization



TECHNOLOGY NAME/TYPE: Lyophilization (Freeze Drying)

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Freezing of waste, sublimation of water vapor, condensation of water vapor, melting of frozen condensate.

SIDE REACTIONS:
Sublimation of other volatile compounds from drying solid

RATE EXPRESSION (IF POSSIBLE):
None reported.

TYPE OF FEED PREPARATION REQUIRED:
None, but waste must be positioned in contact with heat pump interface.

FEED RATE (kg/hr):
To be determined. Processing one partially filled slinger commode collection cylinder per day, assuming a distance between cylinder wall and heat pump interface of 3 cm, average feed rate is 0.25 kg/hr.

TYPE CATALYST/ORGANISMS REQUIRED:
None reported.

PROHIBITED WASTES:
Wastes with collapse temperatures below 230 K may reduce product water quality. Wastes listed under Scenario 3 are not likely to have low collapse temperatures, but testing has not been completed.

TECHNOLOGY NAME/TYPE: Lyophilization (Freeze Drying)

Table 125: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Feces		Solids (10%)	Water (90%)	260	230 to 298	0.1	0.01 to 101.3	24	10 to 40	
Other Wastes		Solids (solids %)	Water (water %)		230 to 298		0.01 to 101.3		10 to 40	Energy cost proportional to amount of water recovered
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:

Scenario 1: Using the vacuum of space rather than a vacuum pump would allow for lower operating pressures, and potentially lower residence times.

Scenario2, Scenario 4, Scenario 5: Freeze drying stabilizes waste and recovers water, but does not produce CO_2. As demand for CO_2 increases, freeze-drying becomes less appropriate.

The bulk of the heat pumped by the thermoelectric modules is associated with phase changes of water; the heat required to raise and lower the temperature of solids in the system is relatively small. As a result, energy use is approximately proportional to mass of water processed, not mass of solids processed. Materials with low and high water content perform similarly in the freeze dryer (assuming that thermal conductivity and vapor diffusivity of the materials are within acceptable limits).

TECHNOLOGY NAME/TYPE: Lyophilization (Freeze Drying)

EQUIPMENT/HARDWARE DATA

Table 126: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Thermoelectric heat pump / condenser assembly	10	0.005	0.15	TBD	
2	Insulated bell jar	10	0.02	0	TBD	
3	Additional cooling hardware	5	0.005	0.15	TBD	
4	Vacuum pump	10	0.005	0.2	TBD	
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 127: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	2	2	2	Linear	Linear	Linear	Based on double flow-rate
2	N/A	2	2	N/A	Linear	Linear	Based on double flow-rate
3	2	2	2	Linear	Linear	Linear	Based on double flow-rate
4	~1	~1	~1	Constant	Constant	Constant	Based on double flow-rate
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: Lyophilization (Freeze Drying)

Table 128: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Dry waste storage container (plastic bag) Used food packaging may be substituted	0.02	1×10^{-5}	0	0	Bag (0.02 kg/24 hr)
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 129: MINOR COMPONENT SCALING FACTORS

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	NA	$2^{1/2}$	$2^{1/2}$	Linear	NA	Exponential	Exp. Based on double flow rate.
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: Lyophilization (Freeze Drying)

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:

Scenario 1: If the vacuum of space rather than a vacuum pump is used the pump can be replaced by a valve, reducing power and mass requirements. Because water and other compounds that volatilize are recaptured by the condenser, the only material vented overboard would be the air in the vacuum chamber at the beginning of the drying step and air from any leaks in the system. To recover air initially in the vacuum chamber, a vacuum pump could be used for a short time at the beginning of the drying step, then replaced by an overboard vent. To reduce power consumption further, a portion of the volatiles could be vented overboard, removing heat from the system.

The lack of gravity presents minor material handling issues. In particular, water from the condenser would need to be removed with a pump, or with a piston pushed through the condenser tube.

Scenario 2, Scenario 4, Scenario 5: As the thickness of the drying layer becomes greater than a few centimeters, processing times increase rapidly. Because of this, the system can only be scaled-up by increasing the length of the heat pump assembly (or by running multiple dryers in parallel), so system efficiency does not vary appreciably with flow rate. Use of phase change condensers rather than thermoelectric modules would decrease the energy requirement of larger systems, but would increase the mass requirement and pose gravity and reliability problems.

A wide variety of materials can be freeze dried, but materials that are stable at atmospheric temperatures and pressures can be air dried at lower energy cost. Freeze drying is most appropriate for feces, food scraps, other biologically active solids, and concentrated wastewaters such as urine, which release undesirable volatiles when dried by other methods.

TECHNOLOGY NAME/TYPE: Lyophilization (Freeze Drying)

Table 130: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The only gravity-dependent process is removal of water from condenser tube. A sliding piston in the tube would allow water to be collected. If a vacuum pump is used in transit, it must function without gravity.
Pretreatment Issues	Solids can be processed, but each batch of mixed waste must contain enough free liquid to deform and make contact with surface of heat pump upon insertion.
Post Treatment Issues	Dry waste should be stored in sealed bags or other airtight containers to prevent rehydration.
Safety	Potential biohazard associated with human waste
Material	Expendable items are the dry waste storage containers and the dry waste itself.
Environmental Issues	During insertion of heat pump and when removing dried waste, odor-causing compounds may be released.
Reliability	Few moving parts aside from vacuum pump
Integration:Technology Interactions	Commode, water treatment system
Integration:Products of Process and their uses	Recovered water will be forwarded to water treatment system.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL = 2. Freeze dryers of many types are currently available commercially, but are generally gravity-dependent, massive, and optimized to produce undamaged dry solids rather than clean water.
Estimated Cost of Development to TRL of 5	Covered under current NRA
Estimated Time & Cost to Manufacture a Unit to TRL of 5	3 years, current NRA
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY ADVANCES:

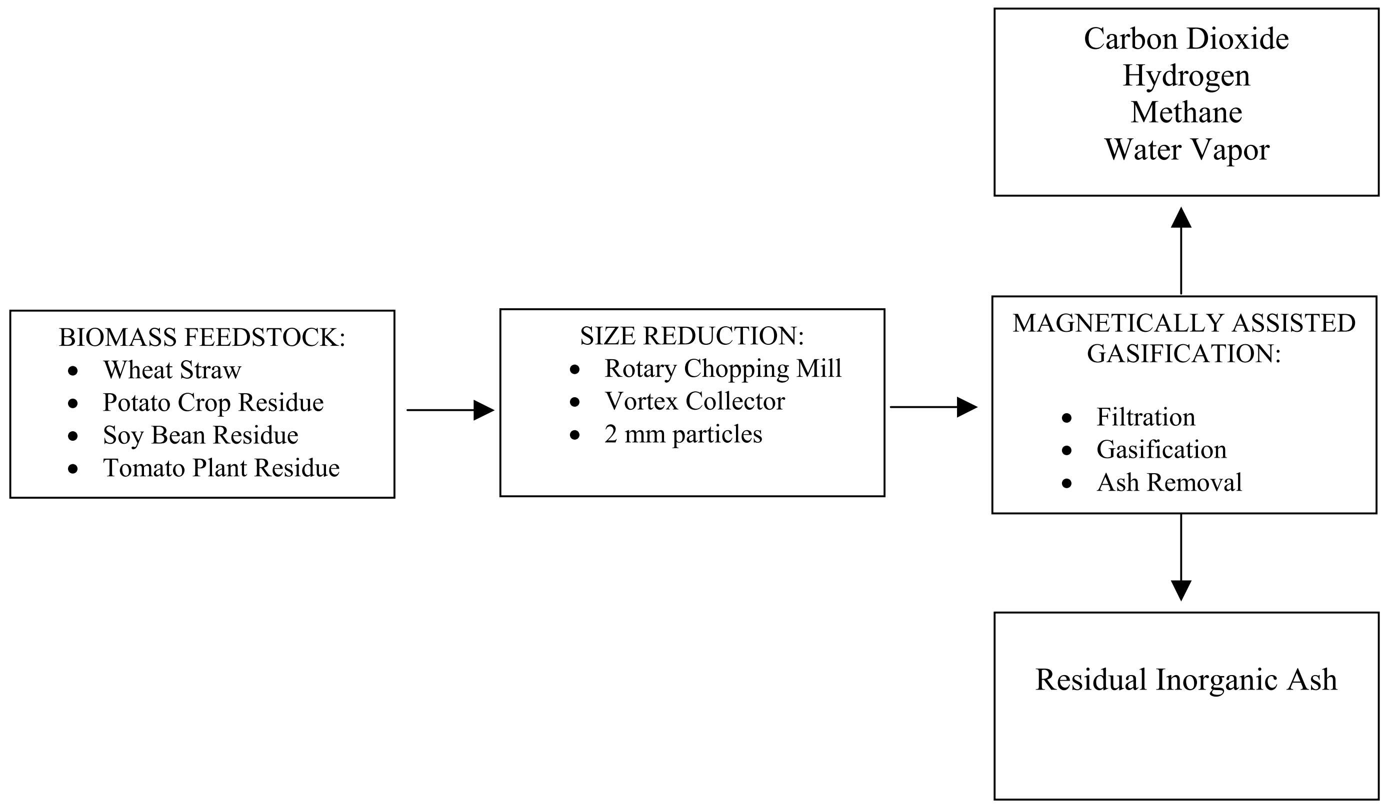
1) What other alternate technologies are comparable to this one?
Other drying methods

2) What other type of technologies would help improve this one?
More efficient thermoelectric heat pumps

3) What other types of work are currently going on to improve this technology?
Measure thermal conductivities and vapor diffusivities of candidate wastes, design and build breadboard system

Magnetically Assisted Gasification (MAG)

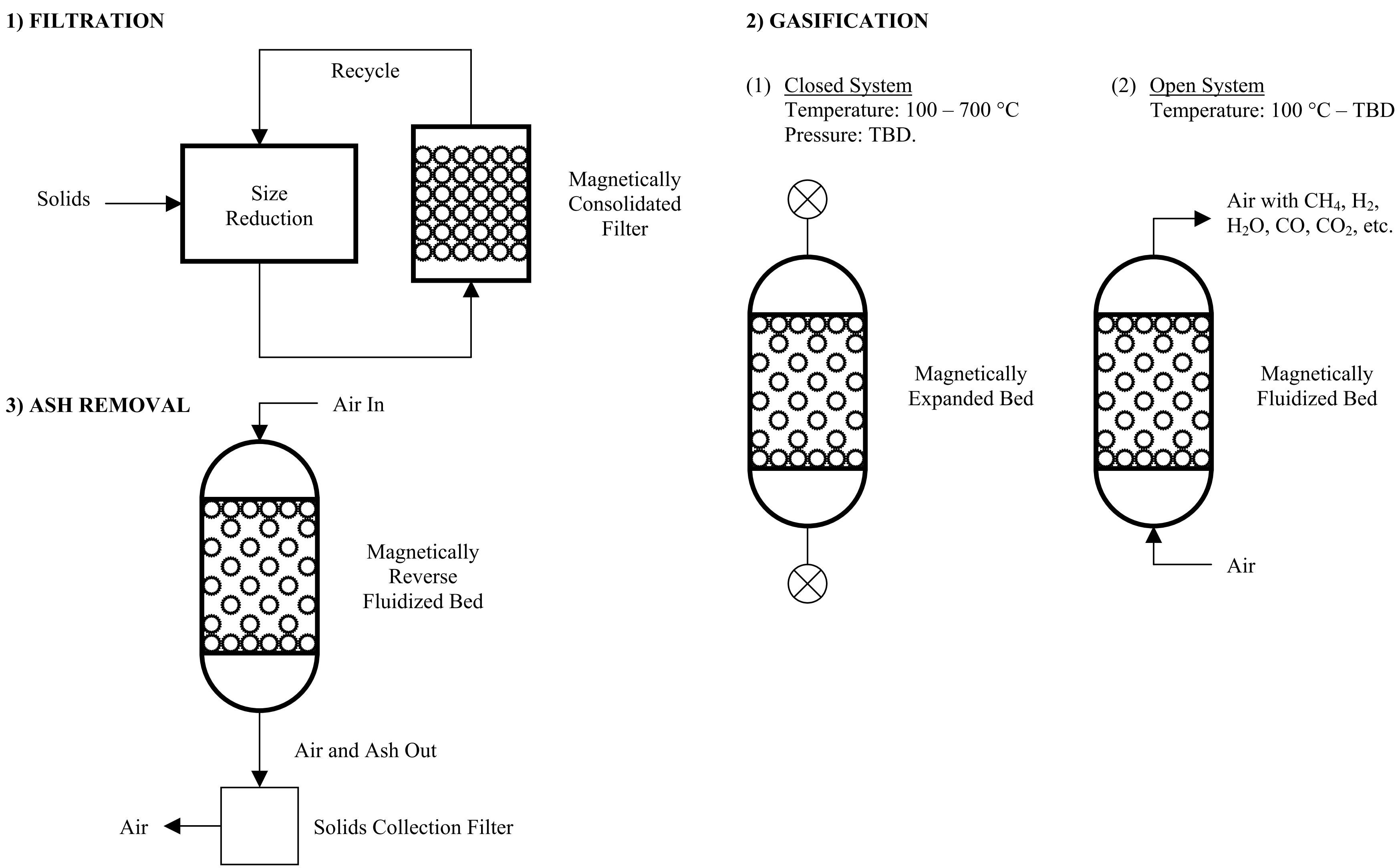
Figure 33: Flow Diagram of Magnetically Assisted Gasification Technology



TECHNOLOGY NAME/TYPE: **Magnetically Assisted Gasification (MAG)**

PROCESS DATA (NOMINAL & RANGES)

Figure 34: Flow Diagram of Processes in Magnetically Assisted Gasification



TECHNOLOGY NAME/TYPE: **Magnetically Assisted Gasification (MAG)**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Pyrolysis
Isomerization
Oxidation

SIDE REACTIONS:
Unknown

RATE EXPRESSION (IF POSSIBLE):
Unknown

TYPE OF FEED PREPARATION REQUIRED:
Crop inedible biomass and other wastes fed as aqueous slurry. The slurry may be very dilute because the solids are concentrated in the process vessel using a magnetically consolidated depth filter.

FEED RATE (kg/hr):
0.5 kg dry weight/hr (estimate)

TYPE CATALYST/ORGANISMS REQUIRED:
At this time, it is not known whether a catalyst will be used. The primary material which must be developed to support this technology consists of ferromagnetic media with high Curie temperatures, i.e., strong magnetic susceptibility at the high temperatures under which the solid waste destruction reactions occur.

PROHIBITED WASTES:
Metals

PROCESS DATA:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Magnetically Assisted Gasification (MAG)**

EQUIPMENT/HARDWARE DATA

Table 131: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Magnetically Assisted Gasification System	50	2	1.0		Preliminary estimates
2	Permanent Magnets					
3	Pressure Vessel					Rated for high temperature and pressure.
4	Microwave or Resistive Heater					
5	Ferromagnetic Media					Rated for high temperature.
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTORS:
None reported.

Table 132: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Pressure Valves					
2	Temperature and Pressure Gauges					
3	Magnet Positioner					
4	Heat Exchanger					
5	Equipment to remove SO_x and NO_x					
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Magnetically Assisted Gasification (MAG)**

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4, and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
None reported

Table 133: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Magnetic field gradients produce forces on ferromagnetic media that compensate for the lack of a normal gravitational force. The intensity of magnetic field gradients can be adjusted to allow operation in 0g, 1g, or hypogravity.
Pretreatment Issues	Particle size reduction and feed of dilute aqueous slurry is required.
Post Treatment Issues	MAG produces a concentrated solid: inorganic mineral ash. Gaseous by-products of gasification reaction operating on organonitrogen and organosulfur species may produce SO_x and NO_x. Secondary oxidation step may be necessary if CO gas is produced. Product gases: hydrogen, methane, carbon dioxide must be separated and routed to other systems for re-use.
Safety	
Material	High temperature/pressure vessel – possibly Hastalloy, stainless steel or titanium.
Environmental Issues	Unknown
Reliability	Unknown
Integration: Technology Interactions	Unknown
Integration: Products of Process and their uses	Hydrogen for reductant in Sabatier or Bosch reactor or as propellant. Carbon Dioxide for plant growth, or water production via the Sabatier or Bosch process. Methane for propellant (or as reductant for destruction of NO_x and SO_x). Water for plant growth, crew, etc.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	1 – 2, Presently being funded through NRA.
Estimated Cost of Development to TRL of 5	$600,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	3 to 6 years and $600,000 to $1,000,000 (minimum)
Other	A tandem system may operate continuously while a single system operates in batch mode (during daylight?).

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) <u>Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.</u>
3) See Figure 2 for TRL definitions.

TECHNOLOGY NAME/TYPE: **Magnetically Assisted Gasification (MAG)**

TECHNOLOGY ADVANCES:

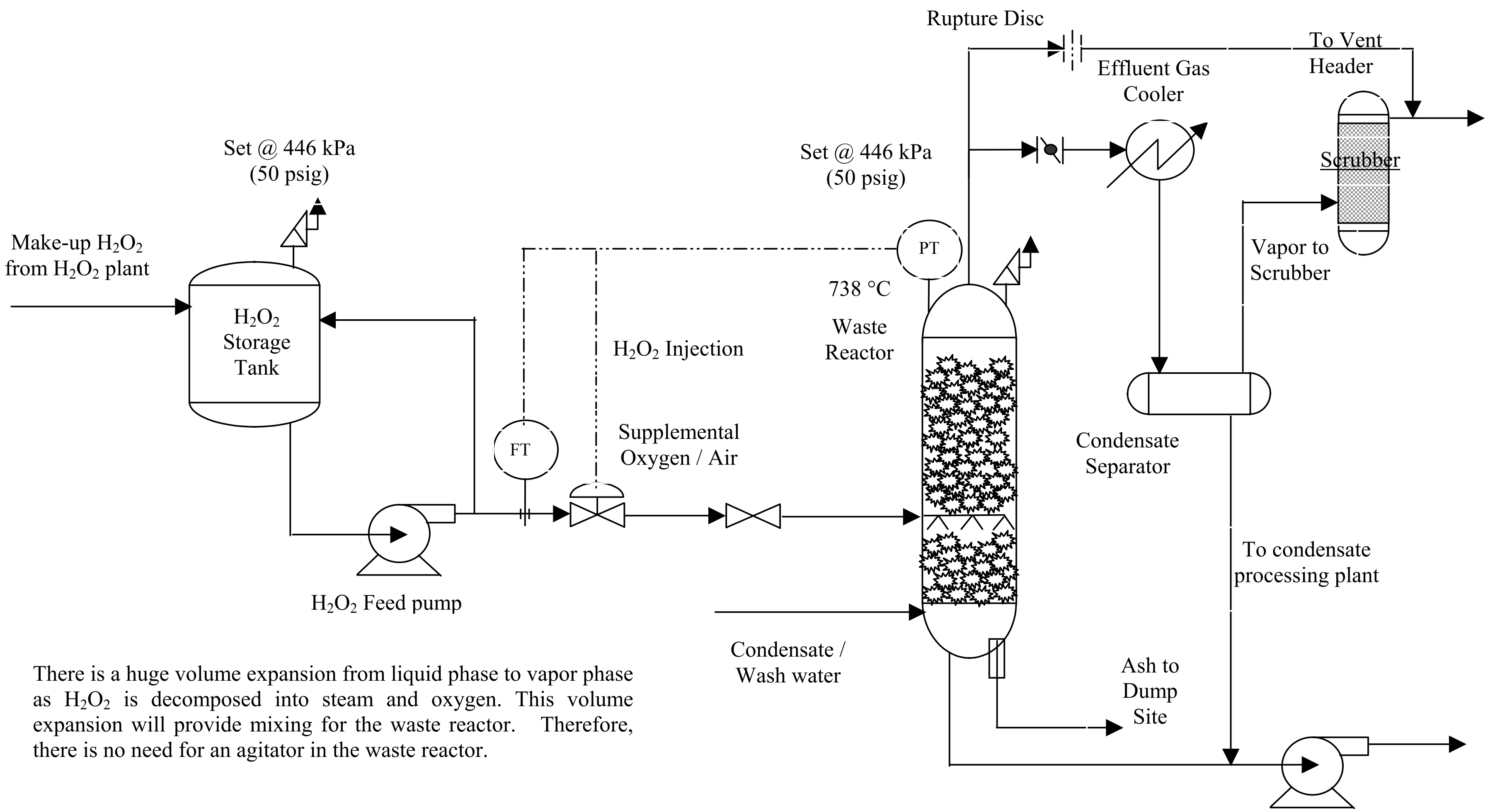
1) What other alternate technologies are comparable to this one?
Supercritical Water Oxidation (SCWO)
Fluidized Bed Incineration
Microwave Incineration

2) What other type of technologies would help improve this one?
Hardware and/or methodology for reducing solid waste to small particle sizes is needed.

3) What other types of work are currently going on to improve this technology?
None.

Peroxide Oxidation

Figure 35: Flow Diagram of Peroxide Oxidation Technology



There is a huge volume expansion from liquid phase to vapor phase as H_2O_2 is decomposed into steam and oxygen. This volume expansion will provide mixing for the waste reactor. Therefore, there is no need for an agitator in the waste reactor.

TECHNOLOGY NAME/TYPE: **Peroxide Oxidation**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Feces combustion: $C_{42}H_{69}O_{13}N_5 + O_2 \Rightarrow CO_2 + H_2O + N_2$
Urine solids combustion: $C_2H_6O_2N_2 + O_2 \Rightarrow CO_2 + H_2O + N_2$
Wash water solid combustion: $C_{13}H_{28}O_{13}N_2 + O_2 \Rightarrow CO_2 + H_2O + N_2$
Inedible plant biomass combustion: $C_4H_5ON + C_6H_{10}O_5 + C_{10}H_{11}O_2 + O_2 \Rightarrow CO_2 + H_2O + N_2$

SIDE REACTIONS:
$N_2 + O_2 \Rightarrow NO_2 + NO + N_2O_5 + N_2O_3$
$S + O_2 \Rightarrow SO_2$
$H_2 + Cl \Rightarrow HCl$
Reaction to remove NO_x: $NO_x + NH_3 \Rightarrow H_2O + N_2$

RATE EXPRESSION (IF POSSIBLE):
None reported.

TYPE OF FEED PREPARATION REQUIRED:
The liquid in wastes should be separated from the solid components to minimize the water content in the waste stream. The solid wastes are then compacted and shredded before they are forwarded to the waste reactor for processing.

FEED RATE (kg/hr):
Solid waste rate: 0.5 to 1.0 kg per batch operation. Each batch operation requires 0.5 to 1.0 hour.
H_2O_2 injection rate: 5.0 to 10.0 mL for each injection. Each injection requires 2-5 seconds. The time interval between each injection may be 15 to 60 seconds depending on the combustion condition.
Air to waste reactor: up to 2,831.7 standard liters/hr (slph) or 100 standard ft^3/hr (scfh). Standard conditions, for purposes of defining units for the volumetric flow rate, are a pressure of 101.3 kPa and a temperature of 288.7 K. (1.0 atmosphere and 60 °F).

TYPE CATALYST/ORGANISMS REQUIRED:
Hydrocarbons in solid wastes will function as catalysts for H_2O_2 decomposition.

PROHIBITED WASTES:
Minimize the water content in the waste stream because water will dilute the concentration of H_2O_2.

TECHNOLOGY NAME/TYPE: **Peroxide Oxidation**

Table 134: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Solid waste	0.5 to 1.0 kg	Some ashes	>99%	1,010	800 - 1,100	101.3	101 - 300		0.5 to 1.0	Refer to Process Flow Diagram
Air	Up to 2,831.7 standard liters/hr			293		300				Refer to Process Flow Diagram
90% (wt) H_2O_2	Rate: 5-10 mL per injection			293	288 - 310	300	300 - 350			Refer to Process Flow Diagram
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
This is a preliminary conceptual design using 90% (by mass) H_2O_2 for waste incineration. The feed flow rates reported are estimates. A mass balance is required once the solid waste composition becomes known. There are three possible operation modes for this technology:

a. Use H_2O_2 as match to initiate the burning, then use supplemental oxygen/air to complete the combustion.
b. Intermittently, inject H_2O_2 together with continuous flow of supplemental oxygen/air.
c. Intermittently, inject H_2O_2 only, no supplemental oxygen/air flow

There is a huge volume expansion from liquid phase to vapor phase as H_2O_2 is decomposed into steam and oxygen. The volume expansion provides mixing for the waste reactor. Therefore, an agitator is not required in the waste reactor..

TECHNOLOGY NAME/TYPE: **Peroxide Oxidation**

EQUIPMENT/HARDWARE DATA

Table 135: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	H_2O_2 storage tank	TBD	Up to 0.00757			
2	H_2O_2 feed metering pump	TBD		Up to 0.75		Consumable: Pump Diaphragm
3	Waste reactor	TBD	0.15			Consumable: H_2O_2 Spray Nozzles
4	Effluent gas cooler				TBD	
5	Condensate Separator	TBD	TBD			
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 136: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1					$(\text{Flow Ratio})^{1.5}$	$(\text{Flow Ratio})^{1.5}$	Note: The Flow Rate scales linearly.
2				Linear			
3					$(\text{Flow Ratio})^{1.5}$	$(\text{Flow Ratio})^{1.5}$	Note: The Flow Rate scales linearly.
1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume. 2) Indicate functional dependence on processing rate. 3) Indicate in the space provided the reasoning for the scaling factors.							

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Peroxide Oxidation**

EQUIPMENT/HARDWARE DATA

Table 137: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Condensate Pump					Consumables: Pump Impeller, Suction Strainer
2	Scrubber					
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 138: MINOR COMPONENT SCALING FACTORS

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1				Linear			
2					$(\text{Flow Ratio})^{1.5}$	$(\text{Flow Ratio})^{1.5}$	

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4, and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA (Tables 179-182) WHICH DIFFERS FROM SCENARIO 3 (*Give descriptions and variations)*:
None reported.

TECHNOLOGY NAME/TYPE: **Peroxide Oxidation**

Table 139: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The waste reactor was designed assuming a Mars surface application. With an alternative design of the spray nozzles, the reactor will operate under microgravity conditions.
Pretreatment Issues	The solid waste feed must be separated from liquid, compacted and shredded before it can be processed with this technology.
Post Treatment Issues	Gas clean-up system and trace contaminant removal systems must be used before allowing the vent gas to emit to Mars atmospheric
Safety	This system is equipped with pressure control valve, vapor line rupture disc and pressure relief valves to reduce the risk of over-pressurizing. The H_2O_2 feed injection valve is on flow control and is reset by the overpressure signal from the waste reactor.
Material	Materials for waste reactor, effluent gas cooler, condensate separator and scrubber must be compatible to a high temperature, corrosive application
Environmental Issues	Gas clean-up system and trace contaminant removal systems must be used before allowing the vent gas to emit to Mars atmospheric
Reliability	The H_2O_2 injection flow control and pressure control of waste reactor are crucial for a safe and reliable operation.
Integration: Technology Interactions	Plant Growth Technology and Biological Solids Handling System will be integrated into one system that will be able to handle all types of solid wastes.
Integration: Products of Process and their uses	Effluent gas could be forwarded to variable pressure growth chamber to provide CO_2 needed for plant growth if it is free of toxic gases.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	1
Estimated Cost of Development to TRL of 5	
Estimated Time & Cost to Manufacture a Unit to TRL of 5	The costs associated with the H_2O_2 production plant and the post-treatment equipment (i.e., the effluent gas cooler, the scrubber, and the condensate separator) may be significant and must be included in the overall estimates.
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See for Figure 2 TRL definitions.

TECHNOLOGY NAME/TYPE: **Peroxide Oxidation**

TECHNOLOGY ADVANCES:
1) What other alternate technologies are comparable to this one?
The following technologies are comparable to this technology:

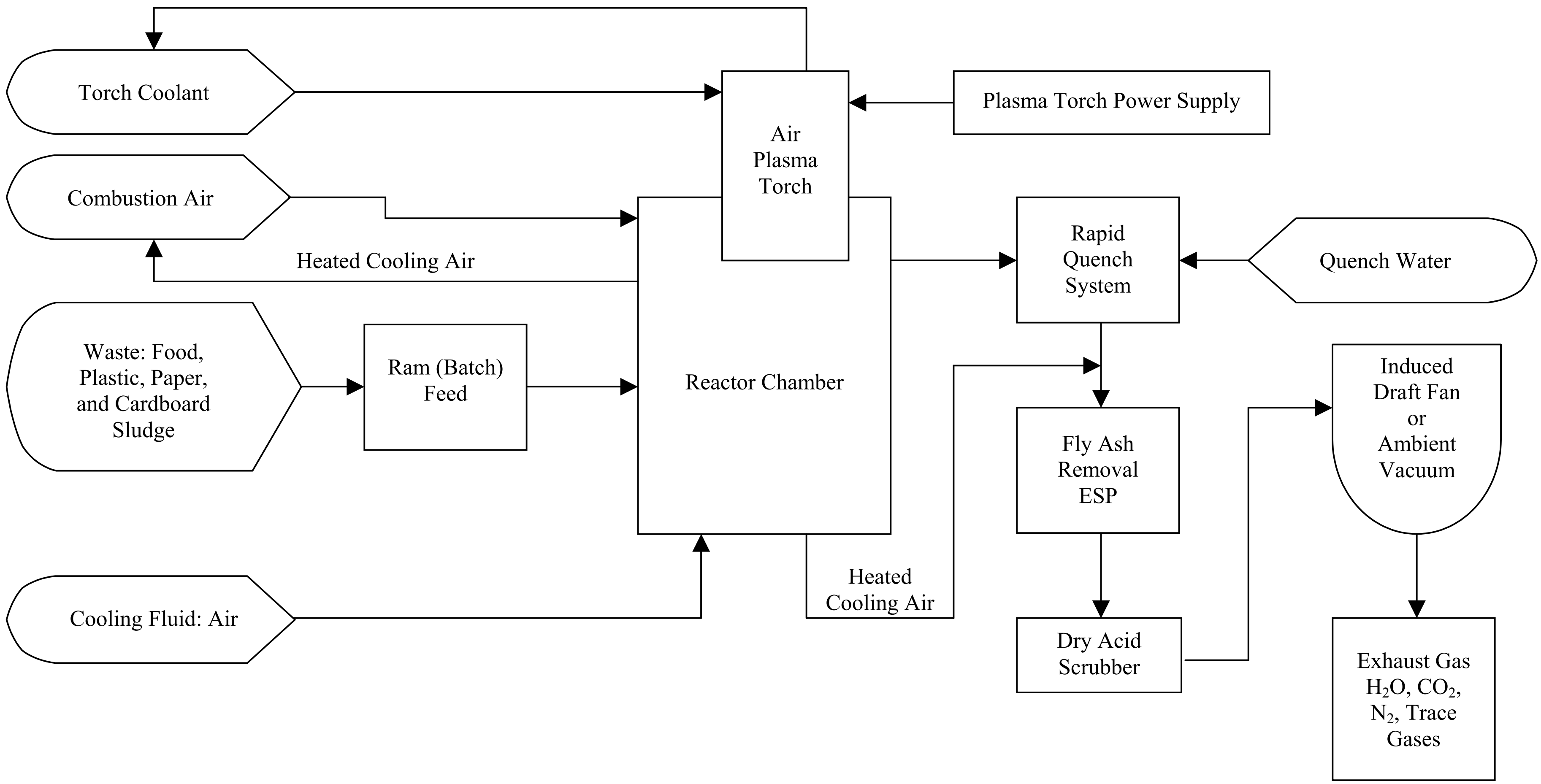
Super Critical Wet Oxidation
Wet Carbonization
Incineration
Plasma Incineration

2) What other type of technologies would help improve this one?
Consider other trace contaminant removal system using zeolite, solid amine, etc.

3) What other types of work are currently going on to improve this technology?
The H_2O_2 feed pump may be eliminated by maintaining a pressure inside the H_2O_2 storage tank with nitrogen or CO_2 as pad gas. The pressurized H_2O_2 tank should be capable of delivering the required flow to waste reactor. Consider options of effluent gas cooler: steam generator or supplemental O_2/air pre-heater.

Plasma Arc Thermal Destruction

Figure 36: Flow Diagram of Plasma Arc Thermal Destruction Technology



TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:

k = ATB exp (-□E/RT) Approximately valid for 1,000-5,000 K

	A	B	Activation Energy □E (kcal/mol)	Process Description
H_2O (l) + M ⇒ H_2O (g)	1.000×10^{2}	0.0	1,000	Vaporization
N_2* + M ⇒ N_2 + M	1.000×10^{7}	0.0	600	Torch Gas
O* + N_2 ⇒ O + N_2	1.000×10^{7}	0.0	600	Torch Gas
O_2* + N_2 ⇒ O_2 + N_2	1.000×10^{7}	0.0	600	Torch Gas
$C_6H_{10}O_5$ ⇒ 5CO + CH_4 + 3H_2	6.170×10^{5}	0.0	16,600	Irreversible
$C_6H_{10}O_5$ ⇒ 4CO + C_2H_4 + 2H_2 + H_2O	2.570×10^{7}	0.0	19,200	Irreversible
$C_6H_{10}O_5$ ⇒ CH_3OH +CH_3HCO +CH_2O +2CO	6.310×10^{7}	0.0	21,300	Irreversible
C(s) + OH ⇒ CO + H	1.330×10^{5}	1.0	35,100	Irreversible
C(s) + O ⇒ CO	5.880×10^{5}	0.0	14,300	Irreversible
C(s) + O_2 ⇒ CO_2	5.880×10^{5}	0.0	14,300	Irreversible
C(s) + O* ⇒ CO	5.420×10^{4}	0.0	0	Irreversible
H_2 + O ⇒ OH + H	1.800×10^{10}	1.0	8,826	
H_2 + O* ⇒ OH + H	1.240×10^{13}	0.0	0	
O_2 + M ⇒ O + O + M	1.850×10^{11}	0.5	95,560	
O_2* + M ⇒ O + O + M	4.230×10^{6}	0.5	0	
OH + H_2 ⇒ H_2O + H	1.170×10^{9}	1.3	3,626	
OH + OH ⇒ H_2O + O	6.000×10^{8}	1.3	0	
H_2 + M ⇒ H + H + M	2.230×10^{12}	0.5	92,600	
H_2O/6.0/H/2.0/H_2/3.0/				
H + OH + M ⇒ H_2O + M	7.500×10^{23}	-2.6	0	
H_2O/20.0/				
H + O_2 + M ⇒ HO_2 + M	2.100×10^{18}	-1.0	0	
H_2O/21.0/H_2/3.3 /N_2/0.0O_2/0.0				
H + O_2* + M ⇒ HO_2 + M	7.00×10^{14}	-1.0	0	Torch Gas
H_2O/21.0/H_2/3.3/N_2/0.0/O_2/0.0				
H_2 + O_2* + N_2 ⇒ HO_2 + N_2	7.740×10^{14}	-1.42	0	Torch Gas
H + HO_2 ⇒ OH + OH	2.500×10^{14}	0.0	1,900	
H + HO_2 ⇒ H_2 +O_2	2.500×10^{13}	0.0	700	
O + HO_2 ⇒ OH + O_2	4.800×10^{13}	0.0	1,000	
O* + HO_2 ⇒ OH + O_2	4.060×10^{13}	0.0	0	Torch Gas
H + O_2 + O_2 ⇒ HO_2 + O_2	6.700×10^{19}	-1.42	0	
H + O_2* + O_2 ⇒ HO_2 + O_2	7.737×10^{14}	0.0	0	Torch Gas

*Up to a total of 243 reactions have been included in model used to predict thermal destruction times.

TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

PROCESS DATA (NOMINAL & RANGES)

SIDE REACTIONS:
See Above. Equations not shown above include NO_x formation rates and intermediate chemical decomposition stages.

RATE EXPRESSION (IF POSSIBLE):
See Above. Chemical analyses show reaction rates can be very fast at temperatures in the 3,000-5,000 K range.

TYPE OF FEED PREPARATION REQUIRED:
Trash gathered in small polyethylene bags. Filled bags would typically weigh 2.3 to 4.5 kg (5 to 10 pounds), about one day's production. Size of polyethylene-filled bags would be to be compatible with ram feeder input requirements.

If sewage sludge is to be processed, it will depend upon the amount of water to be processed, i.e., will some or most of the bulk water be removed prior to treating the sludge. It requires approximately 0.75 kW to evaporate a kg of water per hour. Concentration of solids would be advantageous to lower electrical energy/power requirements; however, the total amount of water to be treated is relatively small. There would have to be trade-off study between the electrical energy required and system complexity to determine the best approach.

FEED RATE (kg/hr):
Production rate of waste is low for six persons, recommend that waste be stored in odor proof polyethylene bags for a period of a week or longer and destroy in a relatively short time. For a relatively small torch of 25 kW, probably should be able to achieve destruction rates of 50 kg/hr. Based upon the generation rate data provide this should allow processing all the combustible trash collected in twelve days.

TYPE CATALYST/ORGANISMS REQUIRED (show amount required per amount of feed to be processed):
None required for the plasma arc process. If preprocessing of sewage sludge to concentrate the solid is performed then some may well be required.

PROHIBITED WASTES:
It is advisable not to process metal trash. While the plasma will melt down all metals and form a clean high-density residue, the presence of metals complicates the operation and there is probably not enough in the waste stream to warrant their inclusion. If the metals include both aluminum and iron thermite, reactions may occur in the oxidizing environment of the concept proposed; these can cause destructive heat release that could damage the system. The aluminum oxide layer formed on the surface of the aluminum will form high-temperature, low-density dross that is difficult to handle. If the metal is associated with packaging, a solution may be to replace it with plastic.

TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

Table 140: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Trash| 5.7 kg/day	Air 40.7 kg/day (Average) This provides 9% excess O_2	Total Ash 0.1 kg/day 12.1 kg/day CO_2 and H_2O created and N_2 pass through	98%	Average 1,500 Torch Temps. are 5,000	1,100-1,700 Torch Temps. are 3,000-7,000	101	101-101.3	10 sec	5-15 sec	Residence time will depend upon feed rate, operating temperature, and moisture content.
Freeze Dried Toilet Waste 0.5 kg/day	Air 1.54 kg/day at 9% excess oxygen	Ash 0.08 kg/day $CO_2 + H_2O$ 0.7 kg/day	84%							
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:

Scenario 1: Infrastructure for transit portion probably would not support the use of a plasma system as described in Scenario 3.

Scenario 2: Infrastructure for transit portion probably would not support the use of a plasma system as described in Scenario 3.

Scenario 4 & 5: The main difference between these scenarios and Scenario 3 is the amount of food that is grown vice how much packaged and the duration of the mission. The percentage of food grown should not have a significant impact on the plasma system (except for a change in the heating value of the waste, because of less reduced plastic packaging). More important issues include the following: are the same amount of personnel involved, does the crew switch and is there an overlap and how much, are there going to be more severe environmental restrictions imposed. In addition to treating waste, could the plasma arc be used for other purposes, for example to produce fertilizer (its original application 100 years ago)? The duration of the mission probably doesn't have a severe impact either, since the operating duty cycle should be quite small, say five hours per two weeks. This translates into 1,300 hrs total run time for the ten-year mission. A land-based system operating 18 hours daily would achieve this in 72 days and current auxiliary system reliability achieves these levels.

TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

EQUIPMENT/HARDWARE DATA

Table 141: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Plasma Torch	40	0.01	33	25	Replaceable Components: Electrodes:4 kg/1,000 hr; Hose/Cables: 5 kg/5,000 hr
2	Torch Power Supply	450	1.4	33	3	Replaceable Components: Electronic Components: 5 kg/20,000 hr; Transformers: 30 kg/20,000 hr
3	Reactor Chamber	400	1.4	0	10	Replaceable Components: Refractory Liner: 200 kg/10,000 hr
4	Electrostatic Precipitator	100	0.8	1		Replaceable Components: Electronic Components: 1kg/20,000 hr; Filters Cleaned or Replaced: 1 kg/100 hr
5	Batch Feeder	50	0.1	manual		Replaceable Components: Isolation Doors: 5 kg/10,000 hr; Ram: 5 kg/10,000 hr
6	Ash Handling System	60	0.1	manual		Replaceable Components: Isolation Doors: 5 kg/10,000 hr; Removable Ash Receptacle: 0.5 kg/20 hr

1) Indicate if subassembly would need replacement at some other interval.

BACKGROUND/REFERENCE INFORMATION:
None reported.

MAJOR COMPNENT SCALING FACTOR:
None reported.

TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

EQUIPMENT/HARDWARE DATA

Table 142: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Induced Draft Fan	25	0.1	0.4	0.04	Replaceable Components: Bearings: 1 kg/20,000 hr; Electric Motor: 10 kg/10,000 hr; Fan Blades: 2 kg/10,000 hr
2	Cooling/Quench Water Pump	25	<0.1	0.4	0.04	Replaceable Components: Bearings: 1 kg/20,000 hr; Electric Motor: 10 kg/10,000 hr; Pump Impeller: 2 kg/10,000 hr
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
Not applicable - not thought to be practical for Scenarios 1 & 2.
No significant differences for Scenarios 3, 4, & 5.

TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

Table 143: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	Gas flow through system should be pressure driven. Position of feed during destruction process may pose a problem in low-gravity environment. A plasma arc system has never been operated in a low-gravity environment so there could be some unexpected impacts.
Pretreatment Issues	Waste should be gathered and placed in odor-barrier plastic bags via manual operation. Design of bag should ensure it could be placed in a ram feed system.
Post Treatment Issues	Information about the quality of the effluent required will be needed to answer this question in detail. Acceptable procedures for handling and disposal of the ash collected in reactor and ESP will need to be developed. The disposal of the carbon dioxide, water vapor and nitrogen will also need to be specified.
Safety	An advantage of the plasma system is that electrical power can be shut off very quickly in case of emergency. As with most thermal destruction processes, the system will have to be designed to limit exposure of crew and habitat exposure to the internal high temperatures and effluent. All surfaces need to be kept at safe temperatures.
Material	No new materials are probably required; however, the development of lightweight, high-temperature insulating material would significantly decrease system size and weight. Longer life electrode materials.
Environmental Issues	Ultimately the system design will be very dependent upon the operating restrictions and compliance issues that will be placed on these manned stations. Disposal of ash and exhaust gases.
Reliability	System must have a high degree of reliability, since it will be the only waste processing system available. Much higher than the current plasma systems now achieve. However, the required duty cycle for the small waste stream volume should be relatively low (Once every two weeks for 3 to 5 hours). Therefore, the reliability of many components should be within current commercial capability.
Integration: Technology Interactions	The components of the baseline system have already been demonstrated in some form, showing that the technology integration issues have been essentially solved.
Integration: Products of Process and their uses	Several plasma arc vendors have advertised that the some of the products of organic thermal destruction could be used. This primarily refers to the syn-gases created (CO and H_2) which could serve as a secondary heat source to operate electric generators, boilers, fuel cells, etc. However, practical reclamation of this energy hasn't been demonstrated at the commercial level. Furthermore, the waste stream of interest is not large enough to provide much fuel. The design proposed does try to recover some heat to improve system efficiency. The use of some of the CO_2, H_2O and N_2 to support plant growth should be viable. It may be possible to operate the system in a mode to produce fertilizer as well.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	TRL 4 Earth-based systems using the technologies required in the concept design already exist. The development costs will be related in designing, building, and demonstrating an isolated manned station design that can be realistically transported, set-up, and operated in the required remote environment. TRL 2 If it is determined that low gravity environments have an impact, then additional research will be required.
Estimated Cost of Development to TRL of 5	Can't answer
Estimated Time & Cost Unit to TRL of 5	Can't answer
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.
3) See for Figure 2 TRL definitions.

TECHNOLOGY NAME/TYPE: **Plasma Thermal Arc Destruction**

TECHNOLOGY ADVANCES:

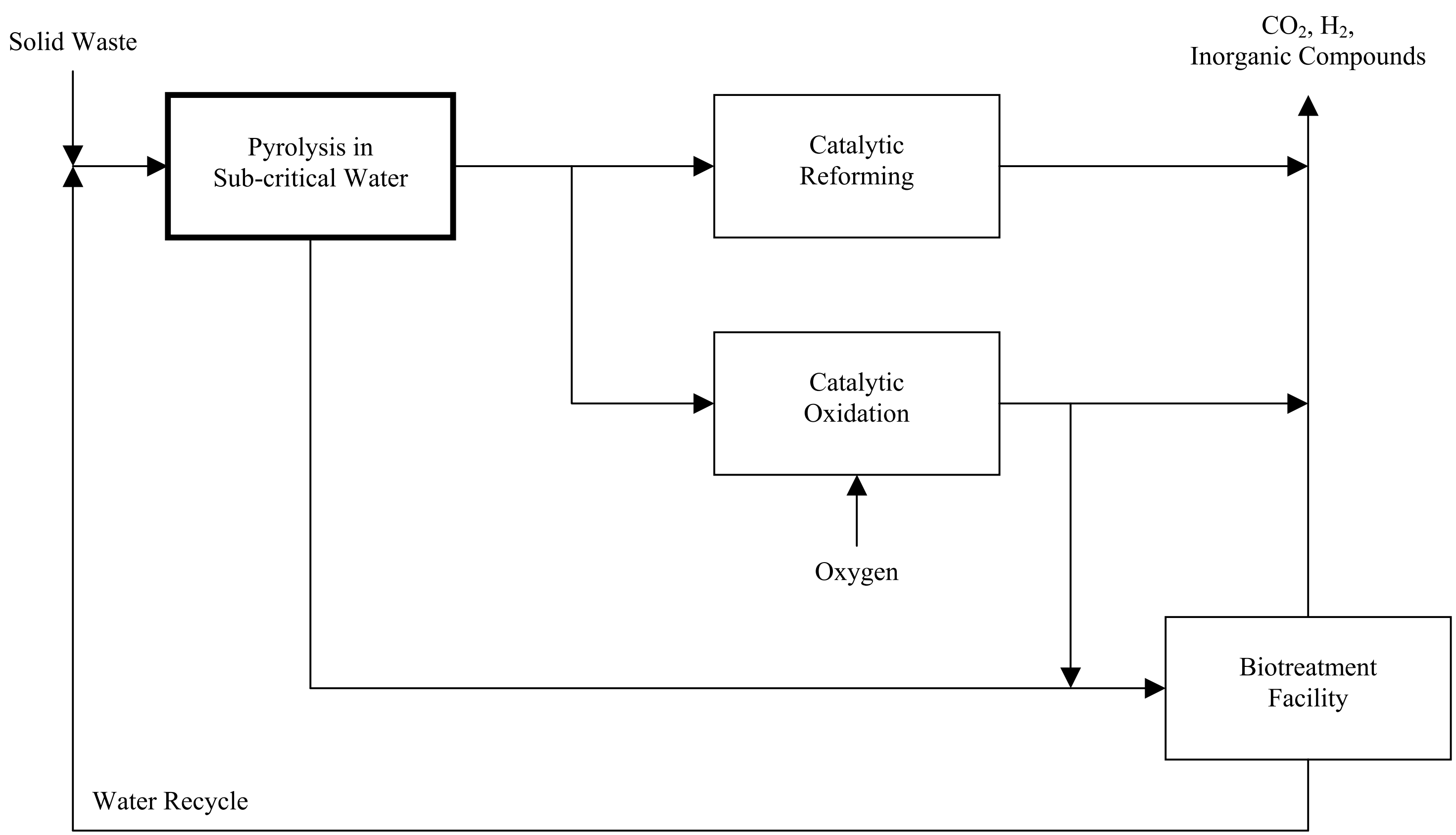
1) What other alternate technologies are comparable to this one?
Electric and microwave furnaces systems should be included in study.

2) What other type of technologies would help improve this one?
Electrodeless methods to generate plasmas, compact and low-maintenance exhaust handling system, high heat capacity and high temperature coolants and lightweight and high operating temperature insulating materials.

3) What other types of work are currently going on to improve this technology?
Several companies are working on the development of commercial plasma arc systems for medical waste destruction, shipboard waste processing, hazardous and radioactive materials treatment, ordnance disposal (e.g., biological, chemical and explosive weapons), etc. This work includes research to build equipment that will operate at a fixed site, can be configured as portable or transportable, and work on moving platforms. These efforts are all directed toward much larger throughputs than required for the NASA extended missions of interest. The development of technologies listed in 2) would be of interest to these applications.

Pyrolysis in Sub Critical Water

Figure 37: Flow Diagram of Pyrolysis in Sub Critical Water Technology



Editor's note: The assessments here appear to focus on the reactor for Pyrolysis in Sub-Critical Water and ignore the other components. Rather, the other components illustrate how such a reactor might fit within an overall waste processing system.

TECHNOLOGY NAME/TYPE: **Pyrolysis in Sub Critical Water**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
Decomposition:
C $\Rightarrow$ $CO_2 + CO + CH_4$ + Light Hydrocarbons
H $\Rightarrow$ $H_2 + H_2O + CH_4$ + Light Hydrocarbons
S $\Rightarrow$ $SO_2 + SO_4^{2-}$
N $\Rightarrow$ $N_2 + N_2O + NH_3$
P $\Rightarrow$ PO_4^{3-}

SIDE REACTIONS:
Hydrolysis:
C and H $\Rightarrow$ Liquid and solid organic byproducts.

RATE EXPRESSION (IF POSSIBLE):
k = 0.01 1/s at 250 °C, 100 atm
k = 0.1 1/s at 300 °C, 100 atm

TYPE OF FEED PREPARATION REQUIRED:
Flexible

FEED RATE (kg/hr):
7 kg/hr for the reactor design study conducted for this workshop. Otherwise, feed rate is flexible. At least 40% solid content *should* be possible.

TYPE CATALYST/ORGANISMS REQUIRED:
None listed.

PROHIBITED WASTES:
Requires further testing.

TECHNOLOGY NAME/TYPE: **Pyrolysis in Sub Critical Water**

Table 144: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Cellulose	O_2 for catalytic oxidation and biotreatment if aerobic (see Figure 37)		99%	523	523 - 573	10,000		0.2		
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
None reported.

EQUIPMENT/HARDWARE DATA

Table 145: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Reactor	5	0.001			
2	(Catalytic Oxidation Reactor) *					
3	(Catalytic Reforming Reactor) *					
4	Feed Pump					
1) Indicate if subassembly would need replacement at some other interval. 2) * Catalytic oxidation and catalytic reforming are possible downstream processes or post-treatment following sub-critical pyrolysis.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MAJOR COMPONENT SCALING FACTOR:
None reported.

TECHNOLOGY NAME/TYPE: **Pyrolysis in Sub Critical Water**

Table 146: MINOR COMPONENT/EXPENDABLE DATA SHEET:

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Heater	1		2		
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

MINOR COMPONENT SCALING FACTOR:
None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4, and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
None reported.

TECHNOLOGY NAME/TYPE: **Pyrolysis in Sub Critical Water**

Table 147: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	This technology should function efficiently in a microgravity environment.
Pretreatment Issues	It may be necessary to process the solids using, for example, crushing or grinding.
Post Treatment Issues	This technology can interface with other technologies such as biotreatment, catalytic reforming, and/or catalytic oxidation.
Safety	No foreseen problems.
Material	Stainless steel is recommended, but verification is required.
Environmental Issues	Requires careful analysis and identification of the effluent stream.
Reliability	No foreseen problems.
Integration: Technology Interactions	
Integration: Products of Process and their uses	
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	
Estimated Cost of Development to TRL of 5	
Estimate Time & Cost to Manufacture a Unit to TRL of 5	
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY ADVANCES

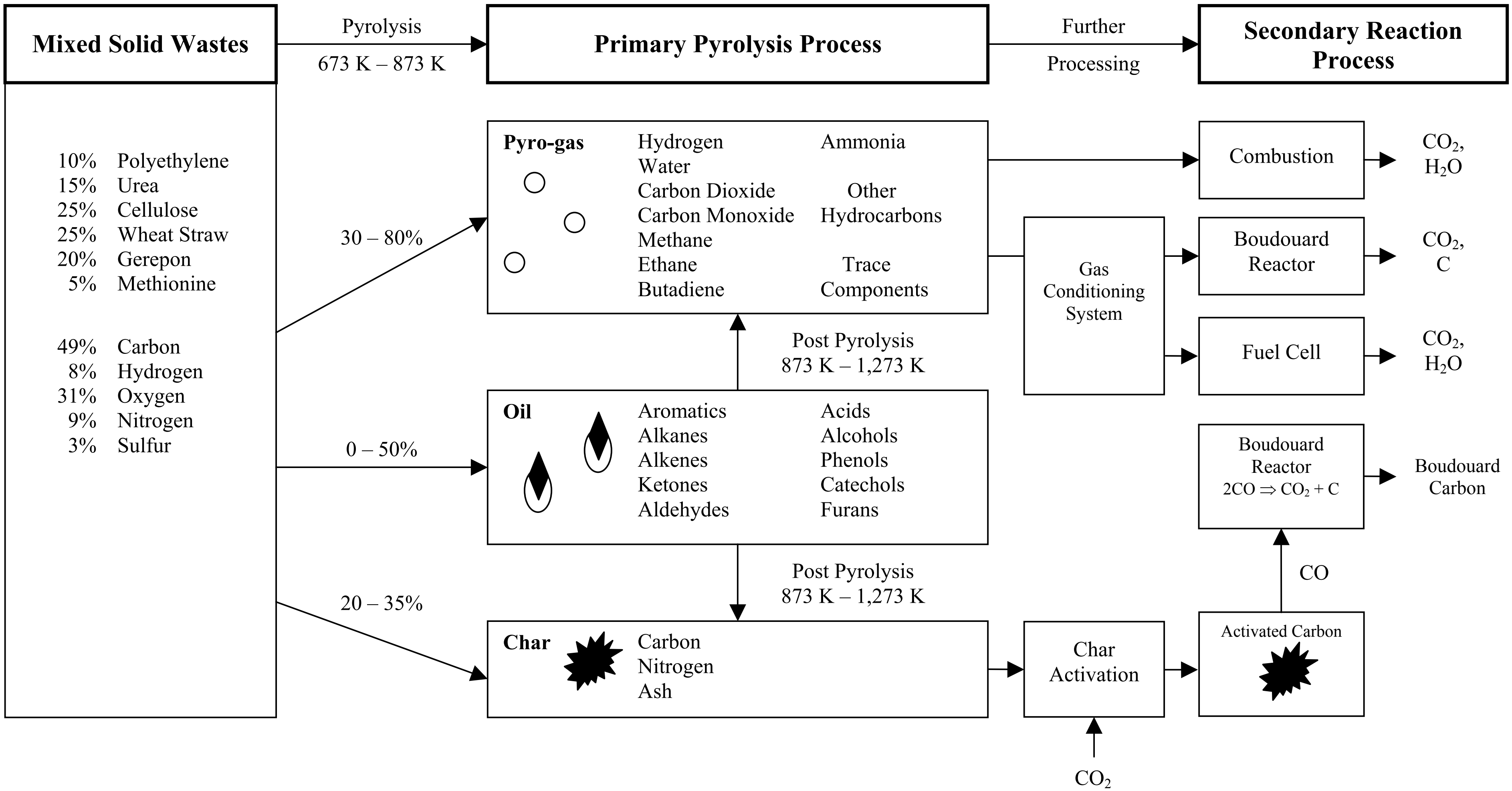
1) What other alternate technologies are comparable to this one?

2) What other type of technologies would help improve this one?
Integration with other technologies such as oxidation and/or biotreatment may be beneficial.

3) What other types of work are currently going on to improve this technology?
Unaware.

NOTE ON FLOW DIAGRAM: The assumed feedstock composition below is somewhat different from the Scenario 3 composition. However, this should not have a large impact on the process design. The scheme outlined for primary pyrolysis is generic to any batch or continuous flow pyrolysis process. Also proposed are various options for secondary reaction processes. Again, these are generic and would apply to other types of pyrolysis processes.

Figure 38: The Pyrolysis Processing Scheme for Solid Waste Proposed by Advanced Fuel Research, Inc.



TECHNOLOGY NAME/TYPE: **Pyrolysis Processing**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS: SOLIDS ⇒ GAS + LIQUIDS + CHAR
The major reaction is the thermal decomposition (pyrolysis) of the mixed solid waste into gases, liquids, and a solid residue in a two-chamber reactor system. Pyrolysis generates a lot of gas (~500 cm^3/g), but a purge gas flow (N_2, CO_2 or H_2O) will probably be used to help stabilize the operating conditions. The liquids pass into the second stage of the reactor system and are further decomposed into more gases and a small amount of residue in a catalytic bed. The solid residue in the first stage can be saved as a means of carbon storage, gasified with CO_2 or H_2O, or combusted with O_2.

SIDE REACTIONS: LIQUIDS ⇒ GAS + CHAR
The overall reaction, including the side reaction, can be approximated by:
$C_7H_{11}0_5 \Rightarrow 3C + 3.5\ CO + 0.5\ H_2O + 0.5\ CO_2 + 5H_2$, if heteroatoms are neglected and an overall composition similar to wheat straw is assumed.

The char can be further gasified by reacting with CO_2, H_2O, or O_2.
$C + H_2O \Rightarrow CO + H_2$
$C + CO_2 \Rightarrow 2CO$
$C + O_2 \Rightarrow CO_2$

RATE EXPRESSION (IF POSSIBLE):

Major Reaction (Primary Pyrolysis):

$$\frac{dx}{dt} = A\ exp\left(\frac{-E}{RT}\right)(x^* - x)$$

where $A = 7.5 \times 10^{11}\ s^{-1}$, $E = 162$ kJ/mole, and $x^* = 0.85$

Side Reaction[16] (Secondary Cracking of Liquids):

$$\frac{dx}{dt} = A\ exp\left(\frac{-E}{RT}\right)(x^* - x)$$

where $A = 4.1 \times 10^{4}\ s^{-1}$, $E = 102$ kJ/mole, and $x^* = 0.35$

Side Reaction (Char Gasification): These reaction kinetics are well known for coal-derived chars but not for waste-derived chars.

TYPE OF FEED PREPARATION REQUIRED:
None, although drying, grinding, and/or compaction may be beneficial, these steps are not required.

FEED RATE (kg/hr):
The current system is a batch process that can handle ~0.5 kg charge in each cycle. The cycle time is estimated to be 0.5 to 2.0 hours. Based on mission Scenario 3, the waste model assumes 10.55 kg/day, which would require 21 processing cycles per day. If the actual cycle time is closer to 2 hours, this would mean that the current system needs to be scaled up by a factor of two.

TYPE CATALYST/ORGANISMS REQUIRED: SEROGEL (dehydrated silica gel) ~ 500 grams. The system will require an initial charge of about 500 grams of a Serogel (dehydrated silica get) catalyst in the second stage.

PROHIBITED WASTES: If chlorine or fluorine is present, they will influence the choice of materials and the design – The design is principally for organic materials that may contain small amounts of inorganic residues.

---

[16] Expression from the work of Cozzani [19].

TECHNOLOGY NAME/TYPE: **Pyrolysis Processing**

Table 148: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (ºK)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Human		<2%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	† See Notes.
Plant		17%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	
Trash		12%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	
Packaging		<2%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	
Paper		<2%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	
Tape		<2%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	
Filters		<2%	100	1,100	900-1,300	1,000	500-2,000	1	0.5-2	
Char	1	<33%	100	1,300	1,100-1,300	1,000	500-2,000	1	0.5-2	‡ See Notes.

* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.
Notes: † Reaction time is only a few seconds at the nominal temperature. Most of the residence time is for heating and cooling the reactor.
‡ Reaction time is several seconds to several minutes at the nominal temperature depending on reactant gas (CO_2, H_2O, O_2), and char reactivity.

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
As illustrated above, pyrolysis processing can be adapted for a wide range of feedstock conditions and the system can be designed to automatically compensate. Most of the common waste materials that have been examined decomposed within a temperature range of 300-400ºC. Consequently, a change of mission scenario will not impact the process design or conditions very much.

EQUIPMENT/HARDWARE DATA

Table 149: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	REACTOR SHELL	20-50	0.002	0.6	0.4	
2	REACTOR INTERNALS	1-2				
3	VALUES	1-2				
4	FLOW REGULATORS	1-2				
5	CONTROL HARDWARE	2-4				

Indicate if subassembly would need replacement at some other interval.
* Note: This listing does not include components that will be required for the gas cleanup system.

TECHNOLOGY NAME/TYPE: **Pyrolysis Processing**

BACKGROUND/REFERENCE INFORMATION:
None reported.

EQUIPMENT/HARDWARE DATA

Table 150: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1				$M^{1/2}$	$M^{1/2}$	Linear	The scaling factor for power demand is less certain (see below).
2				$M^{1/2}$	$M^{1/2}$	Linear	

1) Scaling factor is for sizing components to provide for a larger or smaller system.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.
Note: Depending on the process there may be different scaling factors for power, mass and volume.

BACKGROUND/REFERENCE INFORMATION:
The heat demand for the pyrolysis reactions is dependent on the feed composition. For most of the waste components, the reaction is mildly endothermic and most of the heat demand is for heating the process stream to reaction temperatures. This heat demand will increase if moisture is present. As far as current design is concerned, most of the heat demand is to account for heat loss from the reactor surface and it is not very sensitive to the amount of sample mass. However, this may change as the reactor design is further improved and refined.

MINOR COMPONENT/EXPENDABLE DATA SHEET:
None reported. Note: The reactor design is not sufficiently mature to provide detailed specifications of the minor components.

TECHNOLOGY NAME/TYPE: **Pyrolysis Processing**

Table 151: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The system should not be adversely affected by microgravity conditions and may even benefit.
Pretreatment Issues	There may be some benefit to compacting or drying waste but this is not required.
Post Treatment Issues	The system will produce a storable char residue which can be gasified, combusted, or activated for use as an absorbent. The gases can be vented, stored, used for power generation or chemical manufacture. The gases will need to be scrubbed to remove NH_3, HCl, an HF.
Safety	The system will require venting for possible overpressure, insulation for hot surfaces, and will produce toxic (CO) and combustible (CO, H_2, and CH_4) gases.
Material	The presence of Chlorine / Fluorine and/or wastes containing these elements will influence material selection.
Environmental Issues	None, except for occasional venting of non-recyclable gases in space and ultimate disposal of inorganic residues.
Reliability	Expected to be very good, but unknown at this point.
Integration: Technology Interactions	Plant growth technologies and gas storage technologies.
Integration: Products of Process and their uses	CO_2, H_2O, H_2, CH_4, C, NH_3
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	3, $80,000
Estimated Cost of Development to TRL of 5	$500,000
Estimate Time & Cost to Manufacture a Unit to TRL of 5	2 years, $600,000 including development costs.
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
One of the advantages of the pyrolysis process is that it is relatively insensitive to the composition of the starting mixture. A computerized control scheme can be developed for the pyrolysis system that will automatically compensate for changes in the waste feedstock composition and changes in the desired products.

TECHNOLOGY ADVANCES

1) What other alternate technologies are comparable to this one?

Incineration is comparable in that it is also a thermochemical technique. Incineration is simpler in terms of the range of products but this is also a drawback with respect to pyrolysis which can produce a wider variety of materials. Incineration utilizes a valuable resource, oxygen, and produces undesirable byproducts such as oxides of sulfur and nitrogen. In addition, incineration also will immediately convert all of the waste carbon to $CO2$, which will require venting excess $CO2$. Finally, incineration is not well suited to handle missed waste streams consisting of large un-ground pieces of a variety of materials in different phases and with different heating values.

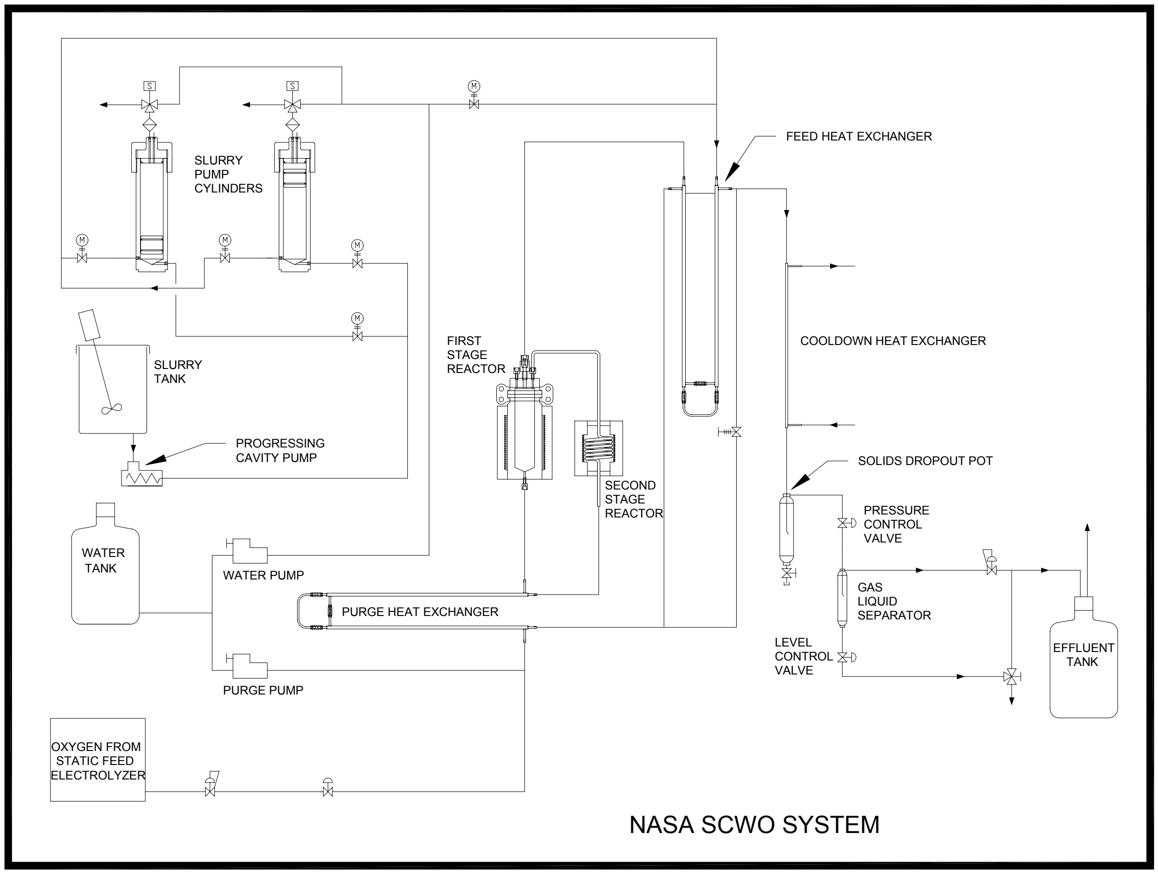
2) What other type of technologies would help improve this one?

This technology will benefit from developments in gas separation, gas storage, waste gas shift reactors, and high temperature fuel cells.

3) What other types of work are currently going on to improve this technology?
There is a fair amount of work going on throughout the world with regard to pyrolysis of plant biomass materials to produce liquid and gaseous fuels. The amount of ongoing work on pyrolysis of animal wastes and waste plastics is more limited. The pyrolysis of mixed wastes has also received limited attention, except for a few studies on municipal solid waste.

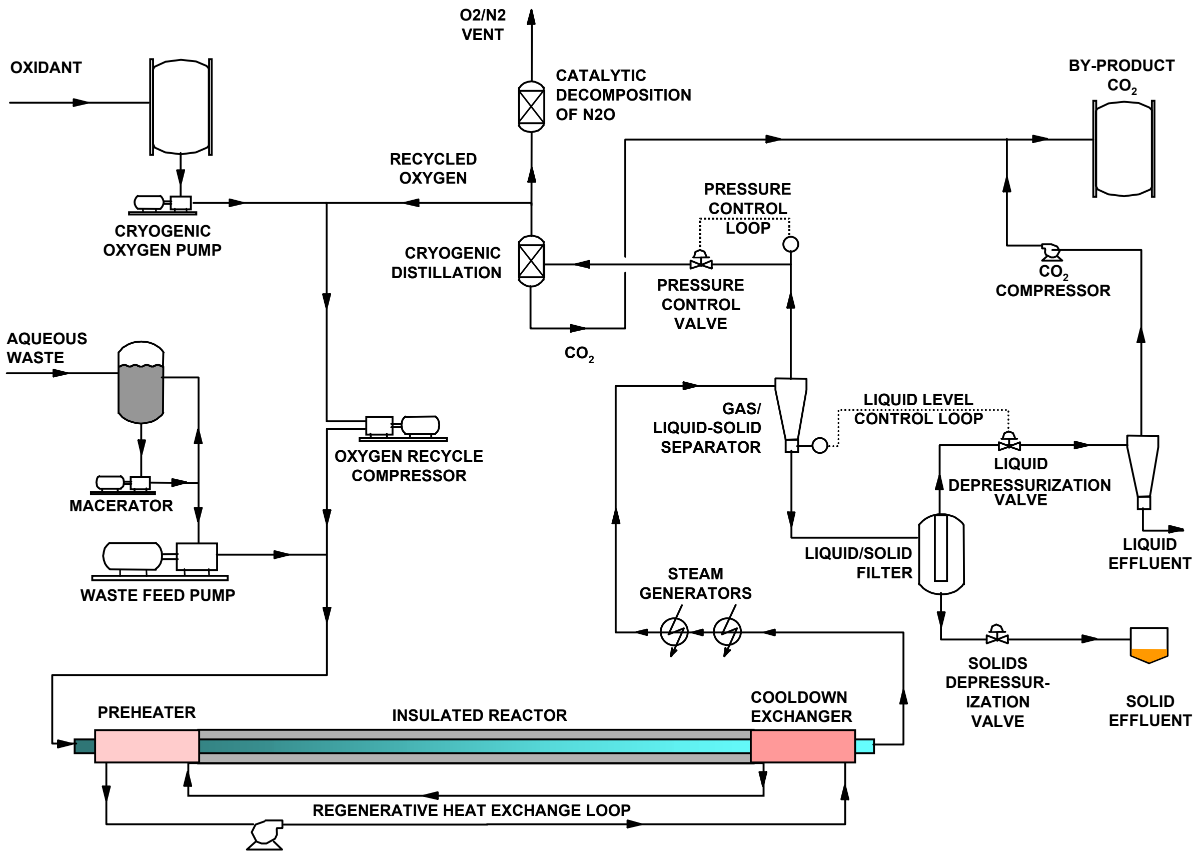
Supercritical Water Oxidation (SCWO)

Figure 39: **Flowsheet of Existing NASA SCWO System**



TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

Figure 40: Flowsheet of SCWO Configuration for Space Applications



TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:
$C \Rightarrow CO_2$
$H \Rightarrow H_2O$
$N \Rightarrow N_2$ (>90%) + N_2O (<10%)
$N_2O \Rightarrow N_2 + O_2$ (catalytic decomposition)
$S \Rightarrow SO_4^{2-}$
$P \Rightarrow PO_4^{3-}$

SIDE REACTIONS:
Organic C ⇒ elemental carbon – Typically negligible under SCWO conditions, but carbon (char) can be formed, if desired, with a first stage reactor and slow heating to 300°C (subcritical).

RATE EXPRESSION (IF POSSIBLE):
Design for about 1 minute at 600°C to reduce residual organic carbon to less than 10 mg/liter.

TYPE OF FEED PREPARATION REQUIRED:
Macerate solids to less than 100 microns
Slurry at a concentration of 4 to 15 wt% suspended solids for a vessel reactor, 4 to 10 wt% suspended solids for a tubular reactor
Slurry pumps have been identified and tested for throughputs of Scenarios 3 to 5.

FEED RATE (kg/hr):
Add wastewater to make slurry of appropriate concentration:
13 kg/hr of 7 wt% slurry for 50% duty cycle (i.e., 12 hr/day on line)
6 kg/hr of 15 wt% slurry for 50% duty cycle (i.e., 12 hr/day on line)

TYPE CATALYST/ORGANISMS REQUIRED:
Possible ruthenium or other catalyst for N_2O decomposition

PROHIBITED WASTES:
Limit organic chlorides, if any, to 1,500 ppm in slurry, or about 1.5 wt% in dry feed.

TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

Table 152: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
All solids and wastewater as a slurry	1.3:1 to 2:1 wt ratio of O_2 in solids	Ash produced at 0.04 to 1 wt ratio	100	873	775-973	23,500	23,500 – 26,000	0.02	0.01 – 0.03	10 to 50% excess O_2.
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
For Scenario 1, which has a relatively high amount of polyethylene, the oxygen to dry waste ratio can be as high as about 2. Oxygen ratio for the other scenarios should stay relatively constant.

EQUIPMENT/HARDWARE DATA

Table 153: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Water, slurry and effluent tanks	15	0.07	None	None	
2	Water and purge pumps	30	0.02	0.2	0.05	
3	Progressive cavity pump/macerator	30	0.02	0.2	0.15	
4	Slurry pump (dual syringe)	100	0.02	None	None	
5	1st stage reactor	50	0.01	None	0.1	Replaceable Parts: Ash canister (see Figure 39) at a rate of 4 kg/10 days. This material should be reusable.
6	2nd stage reactor	15	0.004	None	None	
7	Heat exchangers/steam generators	12	0.01	None	1 - 3	
8	Oxygen compressor/accumulator	300	0.06	0.2	0.05	
9	Solids dropout pot and gas/liquid separator	3	0.002	None	None	
10	1st and 2nd stage reactor heaters	8	0.025	0.05	0.02	
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

EQUIPMENT/HARDWARE DATA

Table 154: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	n/a	<2	2	n/a	Not Known	Linear	
2	2	0.6	0.6	Linear	Exponential	Exponential	
3	2	0.6	0.6	Linear	Exponential	Exponential	
4	n/a	0.6	0.6	n/a	Exponential	Exponential	
5	n/a	0.8	0.8	n/a	Exponential	Exponential	
6	n/a	0.8	0.8	n/a	Exponential	Exponential	
7	n/a	0.8	0.8	n/a	Exponential	Exponential	
8	n/a	0.6	0.6	n/a	Exponential	Exponential	
9	n/a	0.8	0.8	n/a	Exponential	Exponential	
10	0.8	0.6	0.6	Exponential	Exponential	Exponential	

1) Scaling factor is for sizing components to provide for a larger or smaller system.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.
Note: Depending on the process there may be different scaling factors for power, mass and volume.

BACKGROUND/REFERENCE INFORMATION:
Hardware based approximately on SCWO unit built by MODAR for NASA ARC in 1995. For multiple items on a line, numbers given are total of all items. All assessments assume a "Flow Rate" of 2, which corresponds to a doubling of flow rate.

Table 155: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	3 control valves – O_2 flow, system pressure and gas/liquid separator level	10	0.009	Not Known	Not Known	
2	7 motorized on-off valves	15	0.015	Not Known	Not Known	
3	3 regulating valves – 2 for O_2 flow, gas/liquid separator pressure	10	0.009	Not Known	Not Known	
4	3 flowmeters – O_2, water, purge water	Not Known	Not Known	Not Known	Not Known	
5	Slurry tank mixer	15	0.015	Not Known	Not Known	

1) Indicate if subassembly would need replacement at some other interval.

TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

BACKGROUND/REFERENCE INFORMATION:
None recorded.

EQUIPMENT/HARDWARE DATA

Table 156: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	1	1	1	Independent	Independent	Independent	
2	1	1	1	Independent	Independent	Independent	
3	1	1	1	Independent	Independent	Independent	
4	1	1	1	Independent	Independent	Independent	
5	2	0.6	0.6	Linear	Exponential	Exponential	

1) Scaling factor is for sizing components to provide for a larger or smaller system. Note: Depending on the process there may be different scaling factors for power, mass and volume (see Note and Example on page 2 of Instructions for Scaling Factors).
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.

BACKGROUND/REFERENCE INFORMATION:
None recorded.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3:
For scenarios with more solid waste the unit throughput must be scaled up accordingly. Scenario 5 will have 1.64 higher throughput than scenario 3 under the reasonable assumption that slurry concentration is held constant. For some components, there may be design latitude when scaling up. In the case of the dual syringe slurry pump, it is possible to use the same pump size but cycle more frequently. Likewise, for the 1st stage reactor, the size may be minimized by increasing the ash canister change-out frequency. Tanks may also be kept small and filled or emptied more frequently.

As the amount of grown food increases, the CO_2 byproduct from SCWO will become more valuable. The steam generated from SCWO can be used for climate control with the space environment.

In Scenario 5, the oxygen required for SCWO is roughly equal in amount to that generated by the plants. A pressure swing adsorption unit for recovery of O_2 from the plant growth chambers would allow the oxygen loop to be closed and virtually eliminate oxygen as an expendable.

TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

Table 157: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The solids dropout pot, gas/liquid separator, and effluent tank in the ARC SCWO unit depend on gravity. Presumably, these could be replaced with membrane- or centrifugal-type devices. The 1st stage reactor impingement canister is designed for ash that should stick regardless of gravity. The percentage of ash that will stick is, however, an unknown and may necessitate design changes, e.g., tangential feed entry, baffles, or filtration. The tubular reactor is operated at high velocity and should not be gravity dependent.
Pretreatment Issues	Grinding and thick slurry handling require further demonstration for feed concentrations above 10 wt% (vessel reactor). For slurries above about 10 wt%, wet carbonization may be useful.
Post Treatment Issues	The need for N_2O removal from the gas effluent needs to be ascertained with realistic feed mixtures. The water effluent can qualify as potable water if post-treated by reverse osmosis, pH adjustment and ion exchange, which should be straightforward. The quality of ash accumulated in canisters or settled from the liquid effluent must be determined.
Safety	It is believed that safety issues have been adequately addressed by the development work to date.
Material	Materials of construction need to be verified. High-nickel alloys may be acceptable but long-term verification is desirable.
Environmental Issues	CO, gaseous hydrocarbons, NO_x and SO_x emissions are all very low. All effluents should be very clean, including high purity CO_2.
Reliability	Long term testing with realistic feeds is required.
Integration: Technology Interactions	The SCWO system requires electricity to run pumps, the oxygen compressor, heaters, valves, instrumentation and controls, and a mixer. Waste byproducts must be recycled or discarded, and the heat of combustion of the waste material must be used or discarded to the environment.
Integration:Products of Process and their uses	The SCWO unit is capable of converting waste materials to good quality water, minerals, nitrogen and carbon dioxide for reuse.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	3.5 to 4. $1.5MM (NASA only) to reach this level.
Estimated Cost of Development to TRL of 5	$1MM to $5MM
Estimated Time & Cost to Manufacture a Unit to TRL of 5	1 to 2 yr, $1MM to $2MM
Other	

1) Please indicate in the Remarks Section any specific scenario issues that exist.
2) <u>Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both.</u>
3) See Figure 2 for TRL definitions.

TECHNOLOGY NAME/TYPE: **Supercritical Water Oxidation (SCWO)**

TECHNOLOGY ADVANCES:

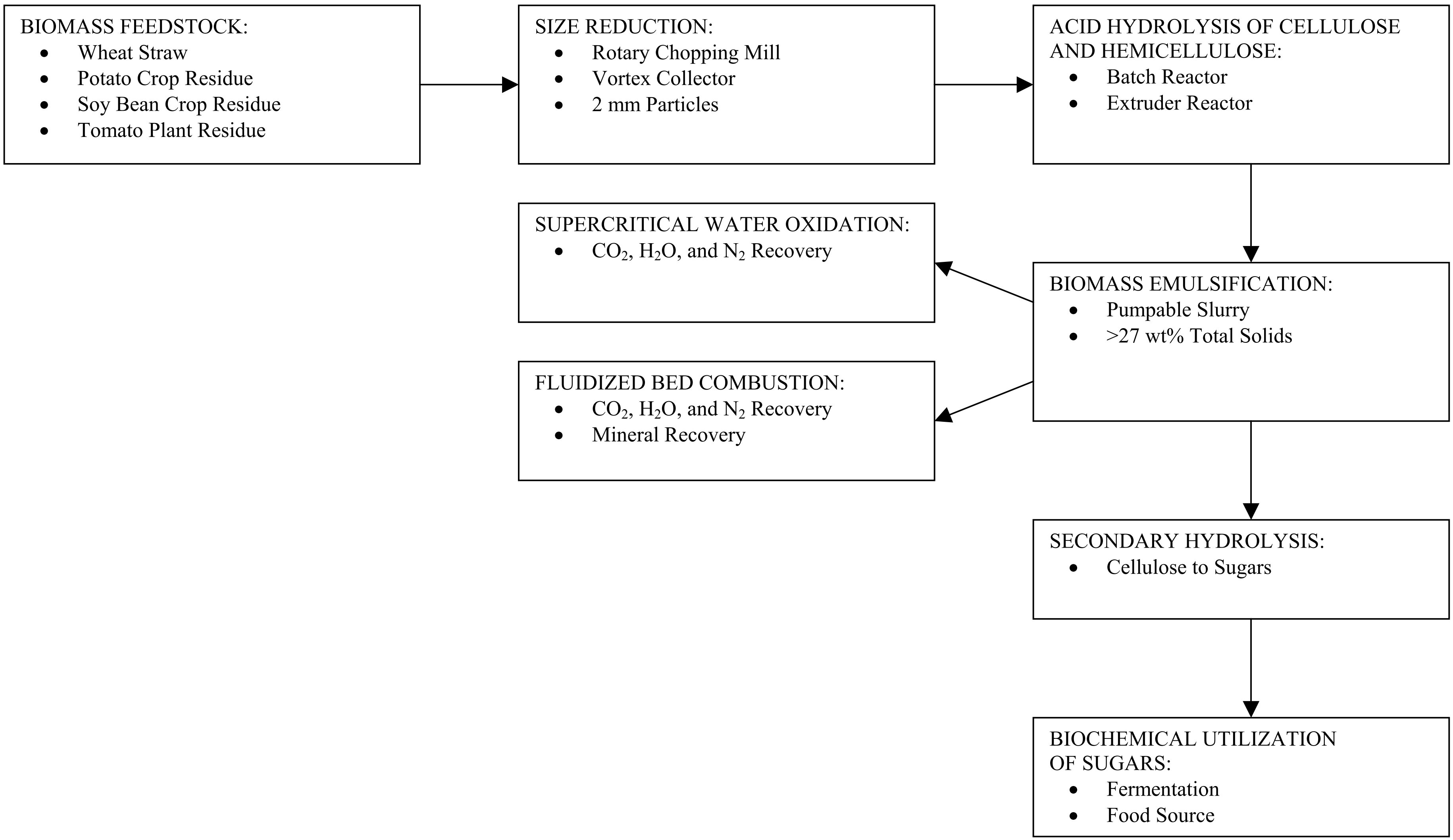
1) What other alternate technologies are comparable to this one?
Wet oxidation is the closest analog, but the byproducts are much dirtier.
Neither incineration nor wet oxidation produce water or CO_2 that is clean enough to be reused.

2) What other type of technologies would help improve this one?
Improved grinding and slurrying methods are very important.
For tubular-type reactor, development of small-scale cleaning devices that can be used online to remove scale that may build up over time.

3) What other types of work are currently going on to improve this technology?
The U.S. Department of Defense currently has several multimillion dollar contracts underway to develop SCWO for waste destruction. Feed streams of interest include chemical warfare agent byproducts, energetic byproducts, slurries of wood and plastic, and shipboard hazardous material. Many other SCWO systems are in various stages of development and commercialization (for terrestrial wastes) around the world, primarily in Japan, Germany, and Sweden.

Acid Hydrolysis

Figure 41: Flow Diagram of Acid Hydrolysis Technology

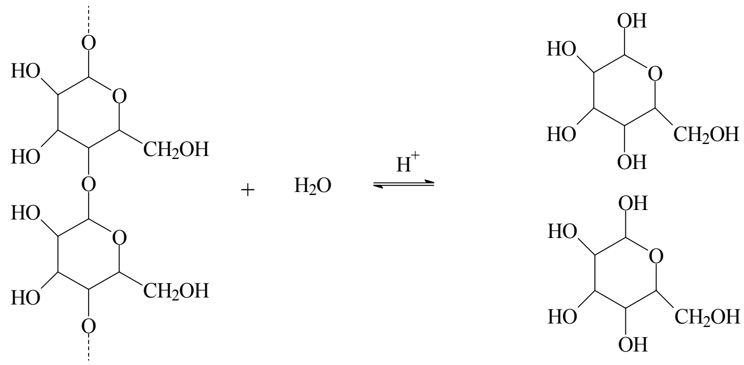


PHYSICOCHEMICAL PROCESSING TECHNOLOGIES

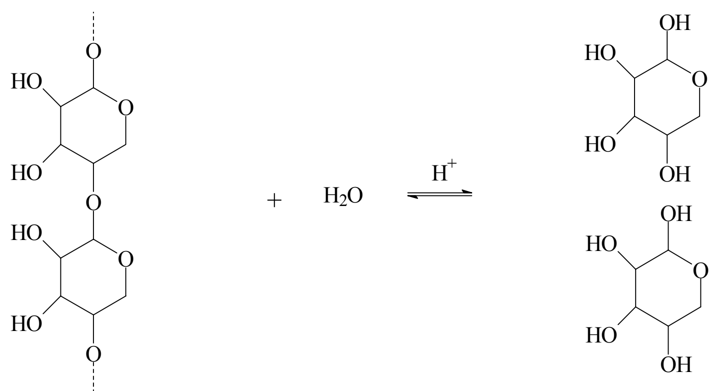
TECHNOLOGY NAME/TYPE: **Acid Hydrolysis**

PROCESS DATA (NOMINAL & RANGES)

MAJOR REACTIONS:

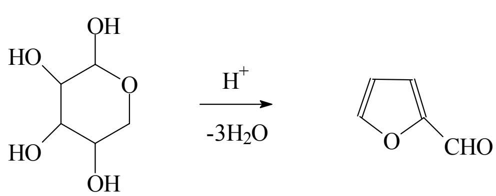


Cellulose Glucose



Xylan Xylose

SIDE REACTIONS:



Xylose Furfural

RATE EXPRESSION (IF POSSIBLE):
Unknown

TYPE OF FEED PREPARATION REQUIRED:
The crop inedible biomass must be chopped to reduce average particle size below 4 mm to facilitate subsequent acid hydrolysis step. Reduction of particle size significantly improves the acid hydrolysis efficiency.

TECHNOLOGY NAME/TYPE: **Acid Hydrolysis**

FEED RATE (kg/hr):
The batch reactor processed 270 g of biomass in 0.75 to 1.5 hours, while the extruder processed between 5 and 25 kg/hr depending on whether acid hydrolysis or alkaline extraction of hemicellulose was the primary process objective.

TYPE CATALYST/ORGANISMS REQUIRED:
No catalysts were tested; however, the use of enzymes such as xylanase and cellulase may significantly reduce operating temperatures and pressures.

PROHIBITED WASTES:
It is assumed that wastes without fibrous cellulose will not be amenable to the direct preparation of high-solids slurries so these wastes will not be considered. Other waste streams (i.e., feces, food wastes, etc.) have not been tested using this technology.

Table 158: PROCESS DATA

Waste/Added Reactant/Product Data				Operating Parameters						
Wastes	*Added Reactant /Waste (Ratio)	Residual Wastes/ Products (Ratio)	Waste Broken Down (Wt %)	Operating Temperature (°K)		Operating Pressure (kPa)		Residence Time Required For Reactants In Process (Hrs.)		Comments
				Nominal	Range	Nominal	Range	Nominal	Range	
Wheat straw, tomato plants, and potato plants	0.002 to 0.012 as sulfuric acid or 0.1 lactic acid and water (i.e., ~1 mole of water for every 2 moles of glucose formed)	<10	>90	453	423-523	690	Unknown	1.5 (batch)	0.05-2.5 (extruder)	Large range of operating conditions reflect the differences between tests with a 1.0 liter batch reactor and an extruder continuous reactor
* Added reactant would be any consumable (O_2, air, N_2, NO_3^-, etc.) required in the major and side reactions of the process. Please indicate stoichiometric excess.										

PROVIDE INFORMATION ON THE OTHER SCENARIOS THAT MAY AFFECT THE PROCESS DATA THAT IS BASED ON SCENARIO 3:
Different scenarios will influence the process data based upon the types of crop residue that must be processed. Different types of fibrous cellulose crop residues will strongly affect the fiber comminution processes, the acid hydrolysis reaction, process conditions, and product quality. The elimination of primary foods such as wheat and potatoes will largely remove difficult to hydrolyze fibers. In addition, application of this technology in microgravity will eliminate the use of the batch process as it is currently configured. The extruder technology may offer gravity independence; however, no data exist for processing in microgravity so no projection of the technology's capabilities can be made.

TECHNOLOGY NAME/TYPE: **Acid Hydrolysis**

EQUIPMENT/HARDWARE DATA

Table 159: MAJOR COMPONENT DATA SHEET

Item No.	Major Component Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Batch Reactor	~35	~0.3	~1.5	0.5	Replacement parts: stirrer (0.2 kg each occasion)
2	Extruder	250	~1.5	~1.5	0.5	Replacement parts: extruder blades (10 kg each occasion)
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION:
None reported.

Table 160: MAJOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor[1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	Unknown			Unknown			
2							

1) Scaling factor is for sizing components to provide for a larger or smaller system.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.
Note: Depending on the process there may be different scaling factors for power, mass and volume.

BACKGROUND/REFERENCE INFORMATION:
None reported.

TECHNOLOGY NAME/TYPE: **Acid Hydrolysis**

EQUIPMENT/HARDWARE DATA

Table 161: MINOR COMPONENT/EXPENDABLE DATA SHEET

Item No.	Minor Component/Expendable Item	Mass (kg)	Volume (m^3)	Power (kW)	Heat Released (kW)	Replacement period (hours, crew-person years or cycles) and comments[1]
1	Mechanical chopper	~40	~0.25	Unknown	Unknown	Replacement parts: chopping blades
2	Vortex separator	~20	~1.0	Unknown	Unknown	
3	Screw feeder	~15	~0.1	Unknown	Unknown	Replacement parts: biomass screw feeder
1) Indicate if subassembly would need replacement at some other interval.						

BACKGROUND/REFERENCE INFORMATION: None reported.

Table 162: MINOR COMPONENT SCALING FACTOR

Item No.	Scaling Factor [1]			Scaling Factor Description [2]			Explanation of scaling factor[3]
	Power	Mass	Volume	Power	Mass	Volume	
1	Unknown			Unknown			
2							
3							

1) Scaling factor is for sizing components to provide for a larger or smaller system.
2) Indicate functional dependence on processing rate.
3) Indicate in the space provided the reasoning for the scaling factors.
Note: Depending on the process there may be different scaling factors for power, mass and volume.

BACKGROUND/REFERENCE INFORMATION: None reported.

PROVIDE INFORMATION ON THE OTHER SCENARIOS (#s 1, 2, 4 and 5) THAT MAY AFFECT THE EQUIPMENT/HARDWARE DATA WHICH DIFFERS FROM SCENARIO 3: Due to the early state of development for this technology, the most efficient form remains uncertain. In particular, the extruder version of this technology appears to offer greater efficiency in terms of time, power, and process simplicity. Importantly, the extruder technology may be gravity-independent, meaning that any microgravity application will require this version of the technology. Significantly, the technology required to efficiently chop and comminute fibrous cellulose biomass crop residues in microgravity has not been developed. Early work with the extruder technology indicates that some preprocessing may be possible in the inlet sections of the extruder (i.e., thermally assisted particle size reduction by shearing/cutting blades). Finally, the types of crop residue will strongly affect acid hydrolysis conditions and process equipment requirements.

TECHNOLOGY NAME/TYPE: **Acid Hydrolysis**

Table 163: PERTINENT CRITERIA/ISSUES

Criteria/Issue[1]	Remarks/Comments
Gravity Dependence[2]	The extruder technology may be gravity independent, while the batch reactor is not. The degree of gravity independence will depend on the extrusion process and its reliance on the weight of material to create a net force on the extrudate.
Pretreatment Issues	Since the biomass must be chopped and shredded, an efficient means to accomplish this task is required.
Post Treatment Issues	The hydrolyzed biomass may be treated by a number of technologies including supercritical water oxidation (SCWO) and incineration. For SCWO the rheology of the treated biomass will be all important, since the valves and tubing within the SCWO reactor must remain open even as the solids loading becomes high. Feeding a fluidized bed incinerator will require close control over solids level.
Safety	Both the batch reactor and extruder are pressure vessels; however, in the latter case, pressures are controlled by both the rotation speeds of the various extruder blades in combination with the inlet pressure. Of secondary consideration will be the acid required to hydrolyze biomass; however the concentration is low (i.e., 1.2 % sulfuric acid).
Material	Acid resistant metals are required that are also resistant to mechanical abrasion. These issues are more critical in the extruder since rapid process times and higher temperatures are preferred.
Environmental Issues	Unknown
Reliability	Unknown
Integration: Technology Interactions	Unknown
Integration: Products of Process and their uses	Sugars may be extracted from hydrolyzed biomass and the efficiency of converting cellulose to sugars improved by a secondary hydrolysis treatment once the cellulose within the fibers has been fully exposed.
Current Technology Readiness Level (TRL)[3] + Development Cost To Current TRL	2 and $70,000
Estimated Cost of Development to TRL of 5	$500,000
Estimated Time & Cost to Manufacture a Unit to TRL of 5	3 years $750,000
Other	
1) Please indicate in the Remarks Section any specific scenario issues that exist. 2) Specifically indicate as to whether the technology is compatible for operation in microgravity, hypogravity or both. 3) See Figure 2 for TRL definitions.	

TECHNOLOGY NAME/TYPE: **Acid Hydrolysis**

TECHNOLOGY ADVANCES:

1) What other alternate technologies are comparable to this one?
Enzymatic degradation of biomass to break down cellulose and/or lignin sufficiently to allow the formation of high solids loaded slurries.

2) What other type of technologies would help improve this one?
Development of thermally stable enzymes for the breakdown of cellulose and lignin may permit much lower operating temperatures and pressures, and higher process rates. Such developments will result in much higher volumetric and energy efficiency.

3) What other types of work are currently going on to improve this technology?
There are some efforts to utilize biomass for the production of commercially important products. A prime example of a potential commercial application is a U.S. Department of Energy (DOE)/New York State Energy Resources Development Authority (NYSERDA) funded industrial collaboration with Biofine Industries to design and build a 1 ton per day pilot plant to covert paper mill sludge into levulinic acid. A continuous process for producing levulinc acid from carbohydrate-containing materials has been patented by Biofine Incorporated and invented by Fitzpatrick (U.S. Patent #5,608,105). According to the patent, a carbohydrate-containing material is supplied continuously to a first reactor and hydrolyzed at between 210-230^{o}C for 13-25 seconds in the presence of between 1-5 wt% mineral acid. The first hydrolysis step produces hydroxymethylfurfural, which is removed continuously and supplied continuously to a second reactor. In the second reactor, the hydroxymethylfurfural is hydrolyzed further between 195-215^{o}C for between 15-30 minutes to produce levulinic acid. 60-70% of the theoretical yield is obtained based on the hexose content of the original feedstock. Short-term industrial uses for levulinic acid conversion include diphenolic acid for plastic intermediates, pyrrolidines/pyrroldinones as ‘green’ solvents and ‘green’ pesticides. Longer-term industrial uses include conversion to 1,4 butanediol, γ-butyrolactone, and tetrahydrofuran for plastics and nylons. In addition, the gasoline additive methyl tetrahydrofuran can be manufactured.

REFERENCES

1. Verostko, C.E., Packham, N.J.C., and Henninger, D.L., “Final Report on NASA Workshop on Resource Recovery from Wastes Generated in Lunar/Mars Controlled Ecological Life Support Systems (CELSS),” CTSD-ADV-035. 1992.
2. Drysdale, A.E. and Hanford, A.J., “Advanced Life Support Systems Modeling and Analysis Reference Missions Document (Draft),” CTSD-ADV-383. 1999
3. Hanford, A.J. and Drysdale, A.E., “Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document,” CTSD-ADV-371. 1999
4. Wydeven, T. “Composition and Analysis of a Model Waste for a CELSS,” NASA TM 84368. 1983
5. Brown, R. “ISS Trash Operations Plan, Team 0 Proposal,” November 4, 1999.
6. Golub, M. A., and Wydeven, T. “Waste Streams in a Typical Crewed Space Habitat: An Update,” NASA TM-103888. 1992.
7. ECLSS Architecture Description Document “ECLSS Architecture Description Document,” Volume 2, Book 2, Revision A, ISS Document D684-10508, May 31, 1996.
8. Stafford K.W., Drysdale A.E., Levri J.A. “Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document (Draft),” CTSD-ADV-383, JSC 39502 Revision A. 2001
9. Grounds P. F., “STS-35 Trash Evaluation Final Report,” NASA TM SP4-91-041. 1991.
10. Grounds P. F., “Beverage Pouches,” NASA TM SP4-91-081. 1991.
11. Strayer, R. F., Finger, B. W., and Alazraki, M. P. “Effects of bioreactor retention time on aerobic microbial decomposition of CELSS crop residues.” Advances in Space Research. **20**:2023-2028. 1997.
12. Shafizadeh, F., Furneaux, RH, Cochran, TG, Scholl, JP, Sakai, Y. “Chemical Reaction Mechanism for Pyrolysis of Cellulosic Materials”. Journal of Applied Polymer Science, Volume 23, pp 3525-3539. 1979.
13. Antal, MJ, Varhegyi, G., “Cellulose Pyrolysis Kinetics: The Current State of Knowledge” Ind. Eng. Chem. Res., 34, pp. 703-717, 1995
14. Pakdel, H., Couture, G., and Roy, C., “Vacuum Pyrolysis of Bark Residues and Primary Sludges”, Tappi Journal, Vol. 77, No. 7, pp. 205-211, 1994.
15. Bruno, C., Walsh, PM., Santavicca, D., and Bracco, FV, “High Temperature Catalytic Combustion of CO --- Mixtures on Platinum”, Int. J. Heat & Mass Transfer, vol.26, No.8, pp. 1109-1120, 1983.
16. Rajeshwar, K., and Ibanez, J., *Environmental Electrochemistry, Fundamentals and Applications in Pollution Abatement*, Academic Press, San Diego, CA, 1997.
17. Sequeira, C.A.C., (ed.), *Environmental Oriented Electrochemistry, Studies in Environmental Science*, Elsevier, Amsterdam, 1994.
18. Tatapudi, P., and J. Fenton, “Electrolytic Processes for Pollution Treatment and Pollution Prevention,” In *Advances in Electrochemical Science and Engineering*, Vol. 4, Alkire, R.C., Gerischer, H., Kolb, D.M., and Tobias, C., (eds.), VCH (Wiley & Sons), Weinham, Germany, pp. 363-417, 1995.
19. Cozzani, V., Petarca, L., and Tognotti, L. Fuel, 74, pp 903-912, 1995.

ACRONYMS

ALS	Advanced Life Support
BET	Brunauer, Emmet and Teller Isotherm
Bio	Biological
BVAD	Baseline Values and Assumptions Document
CELSS	Controlled Ecological Life Support Systems
CSTR	Continuous Stirred Tank Reactor
DSA	Dimensionally Stable Anode
FFB	Fixed Film Bioreactor
FFB	Fixed Film Bioreactor
HEPA	High-Efficiency Particulate Air
HRT	Hydraulic Retention Time
ISS	International Space Station
MSW	Municipal Solid Waste
NRA	NASA Research Announcement
PC	Physicochemical
PPP	Pre- and Post Processing
R&TD	Research and Technology Development
SBIR	Small Business Innovation Research
SCP	Single Cell Protein
SCWO	Supercritical Water Oxidation
SEBAC	Sequential Batch Anaerobic Composting
SMAP	Systems Analysis Modeling Project
STTR	Small Business Technology Transfer
SWM	Solid Waste Management
SWPRR	Solid Waste Processing and Resource Recovery
TRL	Technology Readiness Level
VOCs	Volatile Organic Compounds